DEVELOPING A PREDICTIVE MODEL FOR UNSCHEDULED MAINTENANCE REQUIREMENTS ON UNITED STATES AIR FORCE INSTALLATIONS

GRADUATE RESEARCH PROJECT

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Abstract

The United States Air Force Civil Engineer community continually strives for more descriptive methods to explain the impact of funding decisions on future infrastructure conditions. This paper develops one such method by using linear regression and time series analysis to develop a predictive model to forecast future year man-hour and funding requirements for unscheduled maintenance. The results provide predictive models for up to a five year forecast with improved results for a three year outlook.

Acknowledgments

We would like to express our sincere appreciation to our faculty advisor, Lt Col Stanley Griffis, for his guidance and support throughout the course of this effort. The insight and experience is certainly appreciated. We also want to thank our sponsor, Col Otis Hicks, HQ AFMC/A7, and members of his staff including Mr. Wayne Myers, Ms. Donna Tronerud, Maj Scott Bryant, and Maj Scot Berrian, from the Air Force Materiel Command for their extensive support in data collection for this endeavor. Finally, we want to thank Mr Ron Stoner, the ACES/IWIMS Program Manager for providing civil engineer historical data.

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DEVELOPING A PREDICTIVE MODEL FOR UNSCHEDULED MAINTENANCE REQUIREMENTS ON UNITED STATES AIR FORCE INSTALLATIONS

I. Introduction

Background

On a continuous basis, the United States Air Force Civil Engineer community strives to improve descriptive models for the condition of Air Force infrastructure. These models assist decision-makers in making challenging trade-offs in a limited resource environment. The common question, whether within a government or private organization, “What is the impact if we reduce our infrastructure maintenance and repair investment?” is not easily answered. Intuitively, less investment results in less reliable infrastructure, but then how much investment is enough and what is the cost-benefit analysis? Civil Engineers have long fought against funding shortfalls begging the questions: What is the impact of current funding policies? Is there a predictive model that will quantify with some degree of certainty the infrastructure problems expected based on current investment level? The focus in this effort has primarily been placed on correlating funding provided to Air Force installations for infrastructure maintenance and repair and the backlog of non-recurring sustainment and repair project requirements.

Over the years, the Air Force has developed several models for this purpose encompassing industry standards, engineering analysis, and the subjective assessments of senior leadership, including the Commander’s Facility Assessment (CFA) program, the Facilities Investment Metric (FIM), the Facilities Sustainment Model (FSM), and the Installations Readiness Report (IRR).

However, a fundamental aspect of infrastructure sustainment that receives relatively less attention is that of unscheduled maintenance requests identified by the full spectrum of customers and responded to by organic maintenance specialists. Presumably, the lower relative focus upon this area results from it being a smaller piece of the fiscal pie, but the infrastructure discrepancies revealed in this area present a significant impact to mission accomplishment. A trend analysis of unscheduled maintenance requirements (referred to by the Air Force as Direct Scheduled Work (DSW)), their priorities, and affected systems, will strongly compliment existing analysis methods in predicting infrastructure conditions.

Problem Statement

Can future unscheduled maintenance man-hour and funding requirements be predicted with statistical significance and a degree of certainty based upon known various forms of infrastructure investment?

Research Objectives

Research Objective 1: Develop a funding advocacy tool based upon actual infrastructure failures.

Research Objective 2: Use FIM, FSM, the Interim Work Information Management System (IWIMS), the Air Force Civil Engineer System (ACES), and audit records to develop a predictive model for actual infrastructure failures.

Research Questions

Research Question 1: Can infrastructure failures (as represented by unscheduled maintenance and cost requirements) be forecasted as a function of the preceding level of Operations and Maintenance (O&M) funding invested?

Research Question 2: What predictors are of most significance?

Research Question 3: Can the model help predict future infrastructure condition?

Research Focus

The boundaries of this research will be the financial and infrastructure maintenance and repair records of Air Force Materiel Command (AFMC). We will evaluate possible trends and correlations between funding and budgeted/executed infrastructure projects (predictors) and unscheduled infrastructure maintenance (dependant responses). While the majority of research accomplished thus far has investigated reduced funding impacts upon future major work requirements, we feel significant decision-making information can also be obtained by analysis of the unscheduled maintenance and repair requirements identified and resolved with organic manpower. This category of work can be overlooked as it is accomplished with sunk costs (government manpower and supplies) and executed relatively quickly (within 30 days). However, regardless of cost and time required to fix, these requirements provide an accurate reflection of mission impacting system failures.

In contrast to the majority of the existing body of work in this area, our research will be focused upon the predictability of system failure and related severity, rather than focusing on the resulting fiscal investment required for repair. Specifically, we will research the type of system affected and the priority of the requirement, whether *emergency,* requiring repair within 24 hours, *urgent,* requiring repair within 5 days, or *routine* requiring repair within 30 days.

Theoretical Lens

The primary theoretical lens used by the Air Force is the Lost Service Life Due to Inadequate Sustainment model shown in Figure 1. This model is used to describe the impact of funding sustainment levels at less than 100%. While this theoretical model is often used to describe an intuitive interpretation of the impact of reduced funding, little research has been done to describe the actual mission impacts that result. In other words, referring to Figure 1, we hope to quantitatively describe what is happening inside the shaded area of the graph. Little work has been done in this area; it is this research gap that we hope to fill.

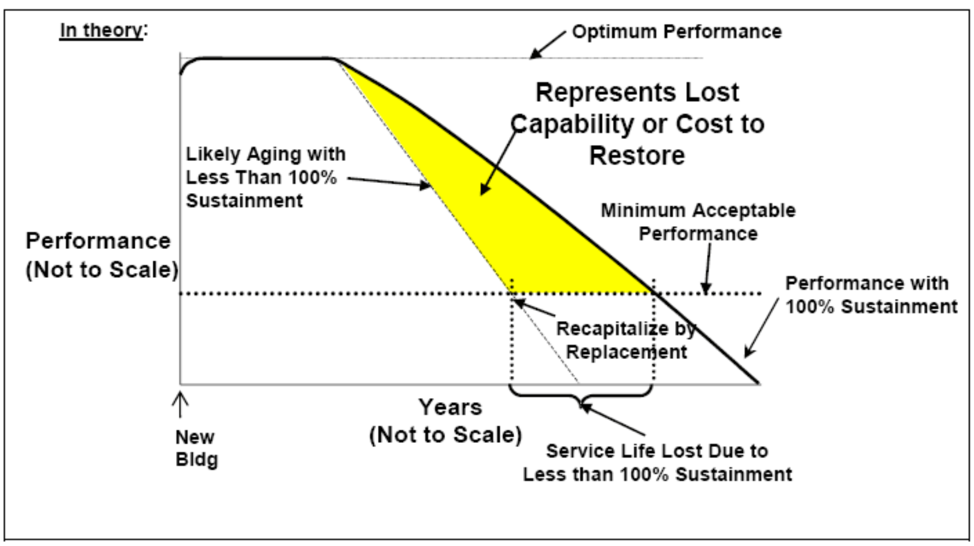

Figure 1: Lost Service Life Due to Inadequate Sustainment (1:12)

Additionally, we will review current Air Force and industry theories for funding facility and infrastructure maintenance and repair. Specifically, we will study the Air Force FSM, FIM, industry standards based on Plant Replacement Value (PRV), formula-based methodology, life-cycle cost methodology, and condition assessments.

Assumptions / Limitations

A few assumptions are required during this research process. First, the specific activities and schedules of base preventative maintenance programs will not be evaluated and are presumed to be designed and executed appropriately. Data from these programs will be considered in the analysis, but judgments regarding the program content itself will not be made. This research assumes Air Force infrastructure preventative maintenance programs developed locally by site-knowledgeable engineers are designed and performed sufficiently. Second, political implications are not considered although they too drive funding and project execution requirements apart from what the condition of the infrastructure may require. For all of these requirements, it is assumed base level engineers are making the correct engineering decisions for these programs. Third, for this model to be effective in future years, we assume funding philosophies will remain constant. The model will need to be adjusted if funding policies change.

Implications

Military preparedness and mission effectiveness will benefit from knowledge of anticipated near-term infrastructure failures. Current management processes are fiscal-centric. Modeling and programming work in this area has focused on predicting the amount of money required in the budget for infrastructure investment. Not surprisingly, many actions in both public and private sector organizations are budget-driven. While the budgeting process cannot be ignored and forecasting methods are very useful in this endeavor, day-to-day operations management can benefit greatly from a predictive model that provides a confident estimate of infrastructure problems that will arise. In this way, senior leaders and engineering technicians can better align constrained manpower, materials, and equipment funding to those areas where the predicted need is greater or of more severe mission impact.

It is unarguably important to estimate funding required in the budget and to provide sound justification for such funding levels, but what is the impact if the funding is not allocated to this area? This has traditionally been a very difficult answer to quantify. It is better to be able to quantify impacts to man-hour and funding requirements associated with the investment than to only be able to state, less specifically, that a system will suffer and that we can expect there will probably be some trouble with it. There are volumes of research describing the appropriate amount of investment in infrastructure in order to sustain it at a preventative maintenance level, i.e. enough money to prevent unscheduled failures. However, there is a gap in the existing body of research in this area when it comes to specifically quantifying and characterizing what will happen with some level of confidence given varying degrees of infrastructure investment.

II. Literature Review

Problem and Context

The results of the literature review conducted thus far have revealed several important pieces of information relevant to this research. First, an overwhelming body of research has highlighted the need for more research on condition-based programs that link funding to a desired infrastructure condition. This area of research has identified the need for condition information to 1) help justify current funding requirements and 2) help predict the impact of a particular investment strategy on future condition. Overall, this literature calls for research describing the link between mission focus, infrastructure condition and funding. Second, a considerable amount of literature focuses on comparing and modeling funding strategies given a set of predictors. However, few documents thus far have in detail explored the effect of specific Air Force funding policies on the future condition of assets. This gap in the research is an area this effort hopes to fill. Third, even though much of the research has focused on funding models, it is still very useful in that it has helped identify certain predictors for this research effort that are common to infrastructure maintenance models. Similarly, and perhaps more importantly, the predictors they didn't use will be considered as well. In particular, the use of actual funding data is one area that it is felt can be improved from previous efforts.

Condition Based Asset Management

Underfunding of facility and infrastructure maintenance is a well-known issue. Substantial facility and infrastructure build-up in the United States during the mid-20th

century is now approaching 60 years of age. Deterioration in these assets began to show in the mid-1970s during the economic downturn of that time. Furthermore, major infrastructure investment tendencies have been in the construction of new facilities rather than re-investment in the existing infrastructure, which contributes to continued degradation (2:24-31). Therefore, extensive research has been accomplished regarding infrastructure maintenance with focus primarily upon predicting future funding required for infrastructure sustainment. However, there has not been emphasis upon predicting the expected tangible results, i.e. infrastructure condition and anticipated failures along with associated mission impact.

Unscheduled maintenance is not well understood and does not receive the attention it deserves considering the sizeable amount of annual operating budgets that are consumed by it. Unscheduled maintenance and repair (M&R) consists of unanticipated service calls and emergency responses that are difficult to forecast. Facility management literature seldom mentions unscheduled M&R and most management software fails to recognize it. Whitestone Research Corporation conducted a study in 1999 that included surveys of facility management organizations. Survey results showed unscheduled repairs accounted for 44% of labor hours committed to annual facility M&R and correlations were confirmed between the influence of budget and staff size, i.e. more of these two resources equated to less unscheduled maintenance. (3:1)

A comprehensive literature review of this subject matter finds common descriptions and methods of facility maintenance. The Air Force has adopted private industry maintenance philosophy and built upon it with tools developed specifically for Air Force application and the government programming and budgeting process. Ronald

C. Cole's thesis, *Analyze the Air Force Methods for Facility Sustainment and Restoration*, evaluated industry approaches to facility management and examined the methods being used by the Air Force (9).

Peter S. Lufkin's article, "Estimating the Restoration and Modernization Costs of Infrastructure and Facilities," in a 2005 issue of *Public Works Management & Policy* identified a generally poor understanding of precisely what funding is required for adequate infrastructure sustainment (13:40-52). The credibility of budget estimates suffers for many agencies since they are typically approximations based upon historical trends and "fair share" distribution across stove-piped departments. Lufkin states estimates based on physical inspections are more defensible but are expensive and more useful for defining remedial projects than estimating future budget requirements. Infrastructure depreciation is also a useful determinate in defining facility restoration and modernization (R&M) requirements for large organizations for which the costs of frequent physical inspections are high. These methodologies are all employed by the Air Force today with budget credibility and successful advocacy of funding requirements constant challenges for military engineers. While the importance of knowing an appropriate amount to budget for infrastructure maintenance in future years is not disputed, insight of probable near term failures by system and degree of severity should not be overlooked for its impact to readiness and mission effectiveness.

For example, Air Force Materiel Command (AFMC) developed a facility infrastructure program with the stated objective of "providing adequate funding that will systematically improve performance and maintain the condition of the infrastructure at the preventive maintenance level." In other words, how much money is required to ensure there are not unscheduled infrastructure failures? This AFMC management process seeks to *determine the required investment* by quantifying the current infrastructure condition on a scale of 0 to 10, with 0 defined as complete failure mode and 10 defined as new condition requiring only future preventive maintenance. One of the more difficult problems with any evaluation process is applying a generic scale to a specific situation and subject to individual interpretations. The process is further complicated because few, if any, projects or systems are composed of a single element. (15:1)

Future Condition

From the existing research on infrastructure degradation, there is a significant body of work focused on modeling future infrastructure states based on sampling data of existing conditions. Overall this area of research seeks to answer important questions pertinent to those concerned with funding infrastructure strategy. One researcher, R.P. Hoskins, identifies an important question as…What will be the effect of a particular policy on the future condition of network assets? The answer to this question, Hoskins argues, is essential to determining the proper infrastructure investment policy. At the same time, Hoskins admits it is difficult to answer. (11:386)

In addition to academic pursuits on future orientation of condition based investment, on-going U.S. Air Force Headquarters Asset Management studies are also leaning toward improved descriptions of system impact resulting from policy decisions (10:3). The Asset Management approach strives to:

1) Help quantify and communicate risk

2) Distinguish data rollup from meaningful portfolio management

3) Advocate for resources

4) Allocate precious dollars where the need is greatest (not fair share)

The focus of this particular research is on further developing item (1) above. Can a mathematical model be developed that will allow us to communicate risk in terms of specific infrastructure concerns anticipated? This research effort hopes to provide an answer to this question.

Dependent Variables

From the numerous articles on maintenance budgeting, lessons on the pertinent variables can be obtained. First, research conducted by Ottoman, Nixon, and Lofgren identified four approaches to estimating sustainment: plant value methodology, formula-based methodology, life-cycle cost methodology, and condition assessment methodology (14:71-83). Public and private organizations use a variety of these methods to determine facility requirements based upon plant value.

Second, Mr. Wayne Myers' briefing to the Air Force Research Lab on 20 Mar 07 describes that previous models for determining the amount of money required to sustain real property have been based upon four primary factors:

1) Previous Execution ($) + Inflation

2) Backlog of Maintenance and Repair Requirements

3) Condition Assessment

4) Percentage of Plant Replacement Value (PRV)

Mr. Myer's briefing also describes the current DoD tool for real property sustainment, the Facilities Sustainment Model (FSM), which is based upon commercial unit costs and business rules. The goals of the FSM are to provide a well documented tool for DoD that puts science, consistency, and audit ability behind the numbers (12:4).

Considering these various research efforts and Air Force history, several variables have been identified for incorporation into the model trials.

Literature Review Summary

From the literature review, the dominant trend in infrastructure asset management is moving toward effects-based maintenance strategies that focus on funding maintenance to achieve a desired future asset condition. One critical component that must be taken into account in defining a future condition is the predicted number of failures that can be expected given a funding strategy. Taking some extremely valuable lessons from the existing body of academic research and current practices at AFMC and the Air Staff, this research hopes to contribute to that effort by providing a suitable model to predict requirements needed to respond to failures.

III. Methodology

This chapter explains the methodology needed to explore the objectives and questions of this research. The chapter is divided into four main sections that correspond to the steps required in the methodology. The first section describes the selection of predictors of interest needed to appropriately describe the dependent variables in our regression analysis. The second section describes the sources used to obtain the necessary data for regression analysis. The third section describes the regression analysis steps. The fourth and final section discusses the comparison between the results for the regression analysis and the AFMC Infrastructure Condition Assessments.

Selection of the Dependent Variable and the Predictors of Interest

The main objective of this research is to develop a model to predict the effects of infrastructure investment on the infrastructure condition. In this model, the infrastructure condition is represented by actual failures as reported to civil engineer squadrons at seven AFMC installations from Fiscal Years (FY) 2001 through 2007. The predictors of interest in this model represent those variables that potentially influence the actual failures. This section describes the variables to be used in this research.

The dependent variables in this research are the costs and man-hours associated with infrastructure failures within AFMC. By using actual failure data, a description of the effectiveness of current investment and maintenance programs can be evaluated. For this research, failures will be identified by the amount of man-hours and costs associated with Direct Scheduled Work (DSW) requests received by civil engineer units in AFMC. A DSW is defined in AFPAM 32-1004V3 as "…work that generally does not require detailed planning. These work orders are small and require less than 50 man-hours. Direct scheduled work is immediate or routine and can be maintenance, repair, or minor construction not requiring capitalization. In practice, DSWs refer to jobs called in to the Civil Engineer Squadrons by any customer on base. In this respect, DSWs reflect infrastructure failures that cause immediate impact to operations. Once a work request of this nature is received from a customer, engineers then immediately (or "directly") schedule the work for execution.

Even though the work is directly scheduled for execution, given the large number of DSWs requested it is necessary to prioritize the DSWs. Civil Engineers prioritize the DSWs as Emergency, Urgent, or Routine. AFPAM 32-1004V3 defines these terms as follows.

Emergency work is work required to correct an emergency condition that is detrimental to the mission or reduces operational effectiveness. It should be completed within 24 hours of notification. An emergency condition is one that, if not corrected immediately, could result in a major compromise of the mission. An emergency will always include, but is not limited to, failure of any utility, fire protection, environmental control, or security alarm system. (8:13)

Urgent work that is not an emergency, but must be responded to and completed within five workdays of receipt or within five workdays after receipt of material is classified as urgent. Urgent requests might include broken windowpanes, inoperative faucets, missing roof shingles, or inoperative light switches. (8:14)

Routine work is a requirement that does not qualify as emergency or urgent work, but cannot be done by the building custodian and should be accomplished to maintain the standards of an installation. Routine work should be completed within 30 calendar days or during the next scheduled cycle visit to the facility, unless materials are required. Examples of routine work include loose or missing floor tiles, a commode or urinal inoperative when more than one is available, or replacing corroded water faucet handles. (8:14)

There are several items of interest within this failure data. First, it is important to investigate the total number of failures experienced at an installation. Second, and perhaps more importantly, it will be important to investigate the numbers of work orders by priority. Emergency work is of particular interest because it represents failures that are “detrimental to the mission or reduce operational effectiveness.” Third, it is useful to review how much money is spent on the work.

The predictors of interest in this research include those variables felt to have an impact on the number of failures. Eight predictors of interest were used. The predictors of interest include Plant Replacement Value, Recurring Work Program, Work Orders, Sustainment, Restoration Executed, Modernization Executed, Total Executed, and Requirements minus Executed (used to represent a shortage of funds).

Plant Replacement Value (PRV) is defined by the Office of the Deputy Undersecretary of Defense for Installations and the Environment as the cost to replace facilities at current standards. For this research, the PRV represents the size of the installation.

The Recurring Work Program (RWP), as defined in AFPAM 32-1004V2, “…applies to all routine, redundant, recurring work involving real property, real property installed equipment, or systems and other equipment maintained (7:52). By definition, RWP scope and frequency is well known, locations are well established, and materials are available or not required. Recurring work includes operations, service work, and preventive maintenance for which the scope and level of effort is known without a prior visit to the job site each time the work is scheduled. Some RWP will be service or operations related: flightline sweeping or snow-removal are services provided by the horizontal work center of the Heavy Repair Element and are typically work items in the RWP. However, most RWP will be preventive maintenance work; for example, replacing the belts on HVAC equipment on a periodic basis." This predictor represents the amount of preventative actions taken at an installation to prevent failures.

Work Orders are defined in AFI 32-1001 as "planned work, to include minor construction and direct scheduled work, requires detailed planning or capitalization of the real property records." This predictor identifies small scale work that is performed on an installation that could have an impact on future DSWs. (4:5)

Sustainment Executed is defined as "…annual maintenance and scheduled repair activities to maintain the inventory of real property assets through its expected service life. It includes regularly scheduled adjustments and inspections, preventive maintenance tasks, and emergency response and service calls for minor repairs. Sustainment also includes major repairs or replacement of facility components (usually accomplished by contract) that are expected to occur periodically throughout the life cycle of facilities. This work includes regular roof replacement, refinishing of wall surfaces, repairing and replacement of heating and cooling systems, replacing tile and carpeting and similar types of work." (5:20)

Restoration Executed "includes repair and replacement work to restore facilities damaged by inadequate sustainment, excessive age, natural disaster, fire, accident or other causes." (5:20)

Modernization Executed "includes alteration of facilities solely to implement new or higher standards (including regulatory changes) to accommodate new functions, or to replace building components that typically last more than 50 years (such as foundations and structural members)." (5:20)

Total Executed represents all operations and maintenance obligations excluding payroll. This funding is further separated into Program Element Codes (PEC) 78, which encompasses all Sustainment activities, and PEC 76, which encompasses all Restoration and Modernization.

Requirement minus Executed is the difference between the PEC 78 and 76 requirements identified during the programming and budgeting process and the actual amount of money received and spent in the funding categories. This predictor serves to quatify funding shortfalls.

Data Sources

Data on the desired variables is available from a number of sources for FY01-07. Data on PEC Requirements and Obligations and plant replacement value is available from AFMC. Data on the Direct Scheduled Work, Recurring Work Program, and Planned Work Orders is available through the Air Force's centralized Interim Work Information Management System (IWIMS) database managed by the 754th ELSG at Gunter Annex, Maxwell AFB, AL. The data fields include Fiscal Year, Type (Recurring

Work Program, Routine DSW, Urgent DSW, Emergency DSW, Routine DSW, or Planned Work Order), the installation code, the shop (HVAC, electrical, plumbing, etc.), total man-hours, labor costs, material costs, and total costs.

For this research effort, data was collected for eight AFMC installations at which civil engineer operations are not commercially sourced, i.e. they are conducted by in-house government personnel. These locations are: Edwards AFB, Eglin AFB, Hanscom AFB, Hill AFB, Kirtland AFB, Robins AFB, Tinker AFB, and Wright-Patterson AFB. Following thorough inspection of the collected data and consultation with the data providers, the information for Edwards AFB was ultimately discarded from the analysis as it contained obvious errors and omissions.

Data Analysis (Statistical Methods)

The objective for this research is to analyze the relationship between the predictors of interest and each dependent variable as described above. First, we perform simple regression and calculate correlation coefficients and p-values looking at the impact of each of the eight predictors of interest one at a time and their relationship with each of the of the six potential outcomes including: emergency man-hours, emergency cost, urgent man-hours, urgent cost, routine man-hours, routine cost, total man-hours and total costs. To account for potential lagging effects, we run the regression analysis, correlation coefficients and the p-values on each relationship for same year data and data sets representing one through five year lag effects. The regression and correlation analysis helps in three ways. First, we are able to quantify the percentage of variability in the dependent variable contributed by single predictor variables. Second, the process helps identify which predictors may be of particular significance for regression analysis. Third, the correlations and p-values help us look at the significance of individual investment programs.

Second, with the correlation coefficients, p-values, single predictor, p-values and R-Square values, we perform multiple variable regressions using all relevant predictors on each dependent variable and lag year to determine the general models.

Third, as there is the potential for a lagging effect as a result of prior year funding, consideration of time series analysis is taken into account. As described in Applied Linear Statistical Models, 1996, basic regression does not consider relationships between random error terms. For time series data the error terms must be considered. As a result, the second step is to check for correlation between the error terms using the Durbin Watson Test for Panel data testing for autocorrelation. From Applied Linear Statistical Models, "Error terms correlated over time are said to be auto-correlated or serially correlated." (17:497) Further…

> "A major cause of positively auto correlated error terms in business and economic regression applications involving time series data is the omission of one or several key variables from the model. When time-ordered effects of such mission key variables are positively correlated, the error terms in the regression model will tend to be positively auto-correlated since the error terms include effects of missing variables." (17:497)

Using our models found in the third step above, we perform a Durbin-Watson test for panel data using the errors from the models and the Durbin-Watson test statistic formula:

$$d_{pd} = \frac{\sum_{i=1}^{N}\sum_{t=2}^{T}(e_{i,t} - e_{i,t-1})^2}{\sum_{i=1}^{N}\sum_{t=1}^{T} e_{i,t}^2}$$

The Durbin-Watson tests the null hypothesis H_o: $\rho = 0$ against the alternative hypothesis H_a: $\rho > 0$ (17:504). ρ is the autocorrelation parameter. To determine between the alternatives, the Durbin Watson value for panel data (d_{pd}) is compared against a table of upper and lower bounds as described in (19). If d_{pd} is less that the lower bound, then we accept the alternative hypothesis. If, d_{pd} is greater than the upper bound, then we accept the null hypothesis. If d_{pd} is between the lower and upper bounds, then the test is inconclusive (17). After computing d_{pd} and comparing against the tables in (19), we rejected the null.

With the alternative accepted, there are two remedial measures we can take (17). First, we can include more predictors. In our case, we have exhausted all of our predictors. As a result, we must turn to the second measure and transform the data to account for the time series effect and again run linear regression to determine the new model. This is done by the using the formulas: $Y_t' = Y_t - \rho Y_{t-1}$ and $X_t' = X_t - \rho X_{t-1}$ to transform the data. Y and X are the dependent and independent variables and ρ is the correlation coefficient of the error terms produced by the original model.

IV. Results and Analysis

Current Trends

Under current Air Force business practices and levels of resourcing, we observe an upward trend from Fiscal Year 2001 to Fiscal Year 2007 for each of the eight dependant variables investigated as illustrated in the following scatter plots. This is cause for concern as it indicates an increasing requirement for funds and manpower in an environment of constrained resources. For example, total man-hours invested for Direct Scheduled Work at the seven AFMC installations in this study increased from 201,098 hours in FY01 to 1,094,778 hours in FY07. Associated with the man-hour increase is a rise in total costs from $15,539,830 in FY01 to $65,242,772 in FY07; an inflation-adjusted increase of 258% over six years. Figure 2 illustrates the gap between the increasing actual trend line for Total Costs and how the trend would look if only increased by actual inflation in each of the years. Figures 2a illustrates the Total Costs fitted line (or trend line) along with the standard deviation range for the observations in each year. Figures 3-9 follow this pattern for depicting the respective trends for each of the dependent variables analyzed. We recognize these figures may be misleading as there is a pattern in the source data of unexpectedly low cost and man-hour values for FY01 relative to the other years and in some cases there was no data available for FY01, which has the effect of increasing the slope of the trend. However, no matter how you analyze it, the increasing trends outpace simple inflation.

Figure 2: Total Costs Trend Line with Observations and Inflation Line, FY01-07

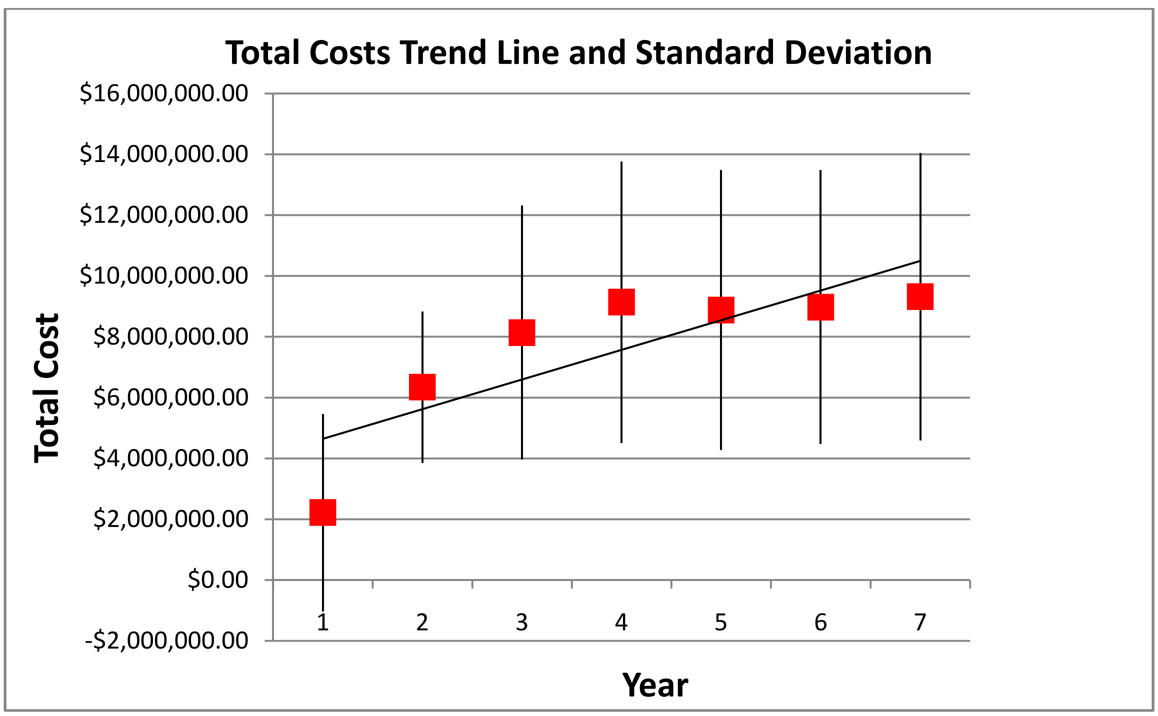

Figure 2a: Total Costs Trend Line and Standard Deviation, FY01-07

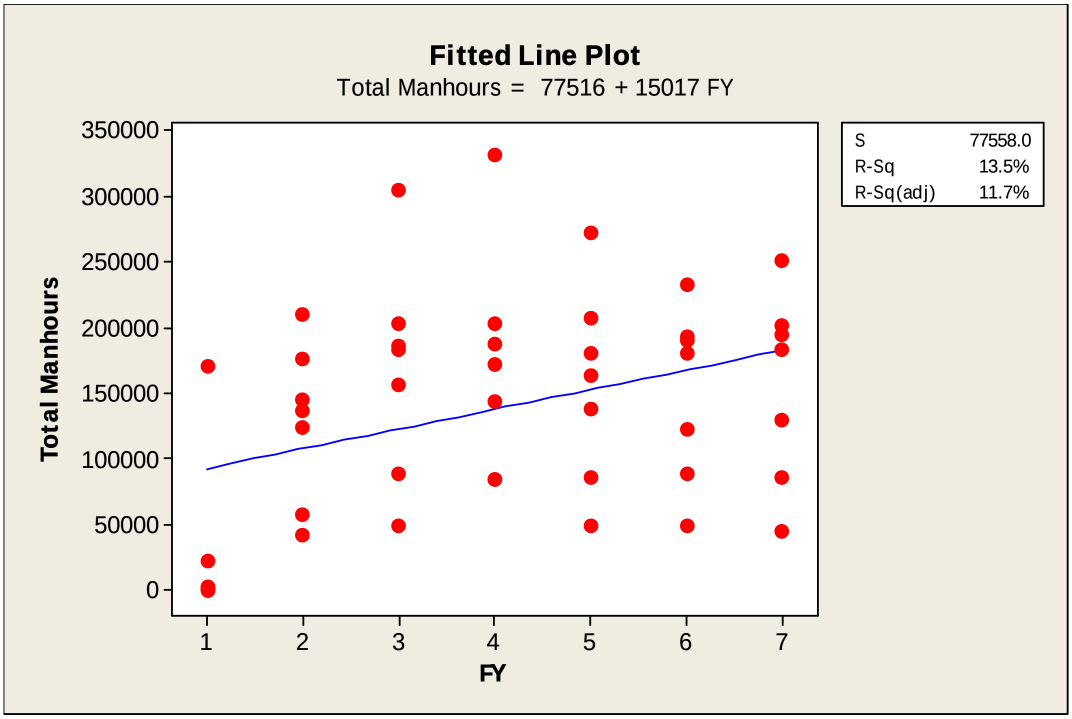

Figure 3: Total Man-hours Trend Line with Observations, FY01-07

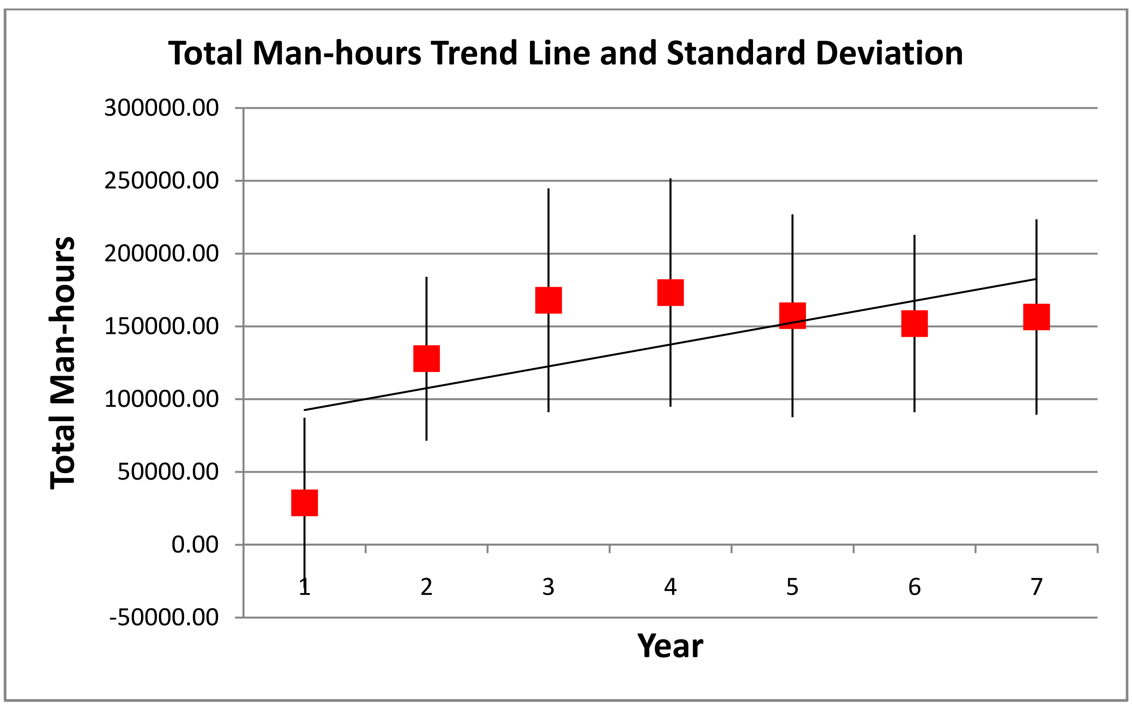

Figure 3a: Total Man-hours Trend Line and Standard Deviation, FY01-07

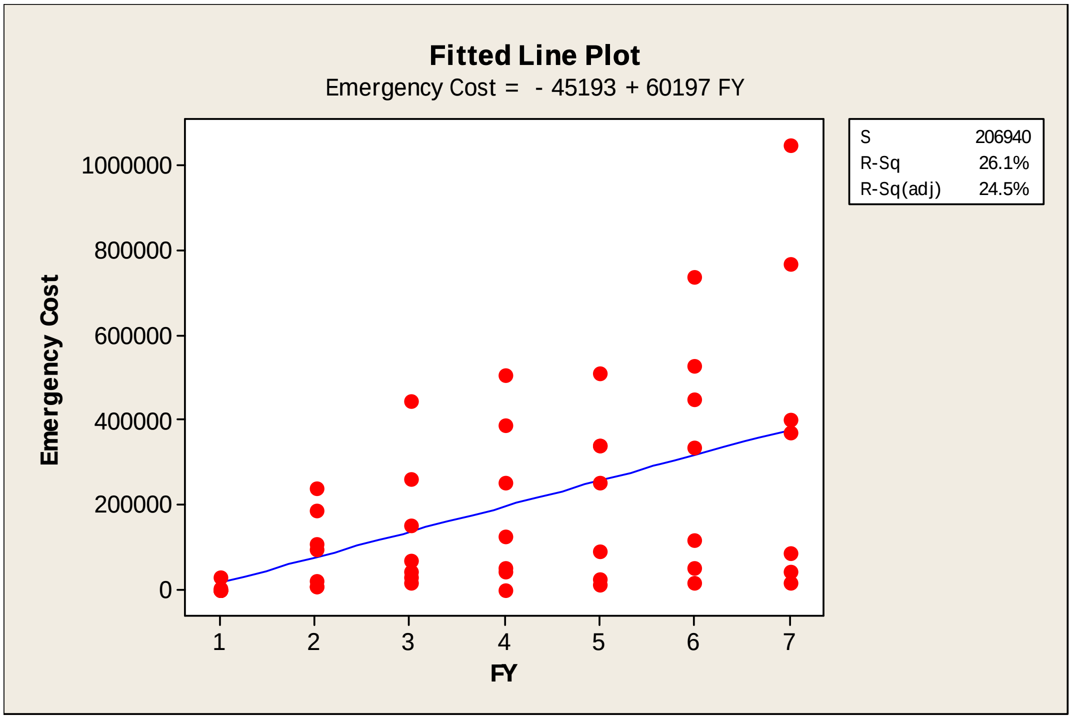

Figure 4: Emergency Costs Trend Line with Observations, FY01-07

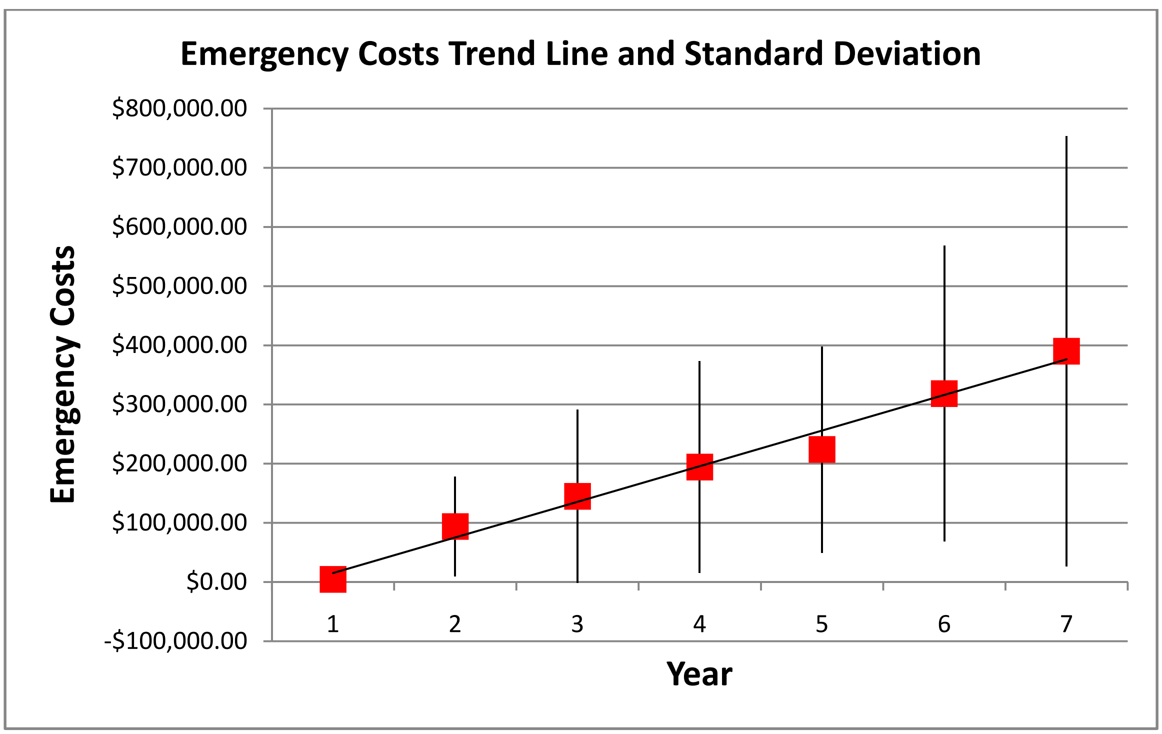

Figure 4a: Emergency Costs Trend Line and Standard Deviation, FY01-07

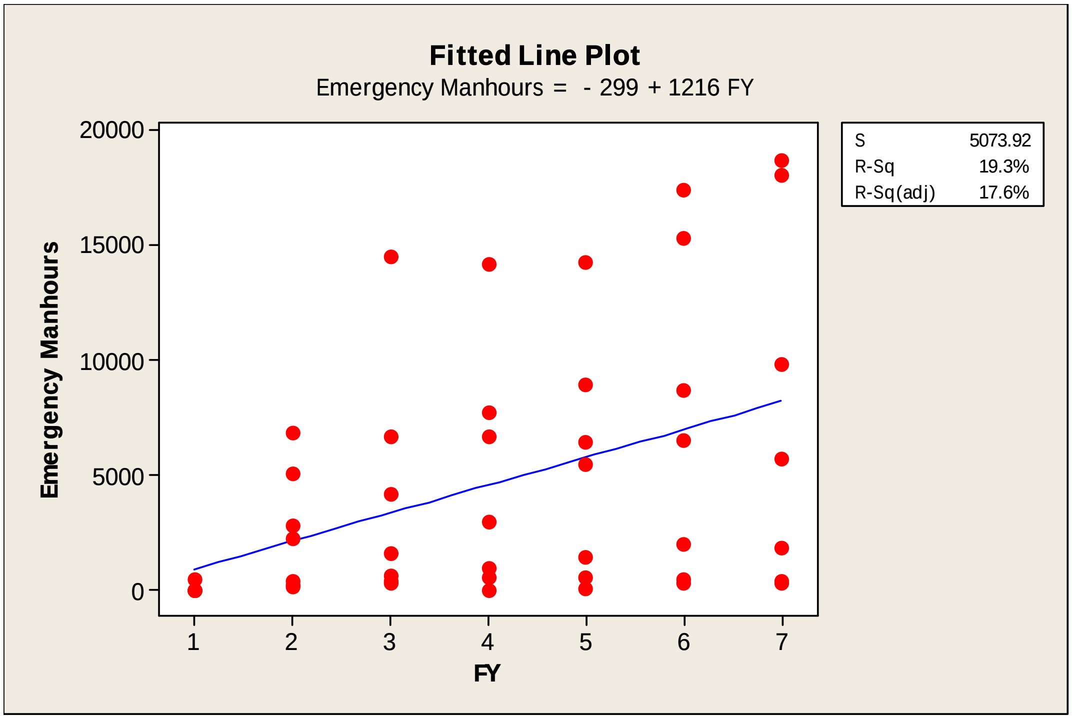

Figure 5: Emergency Man-hours Trend Line with Observations, FY01-07

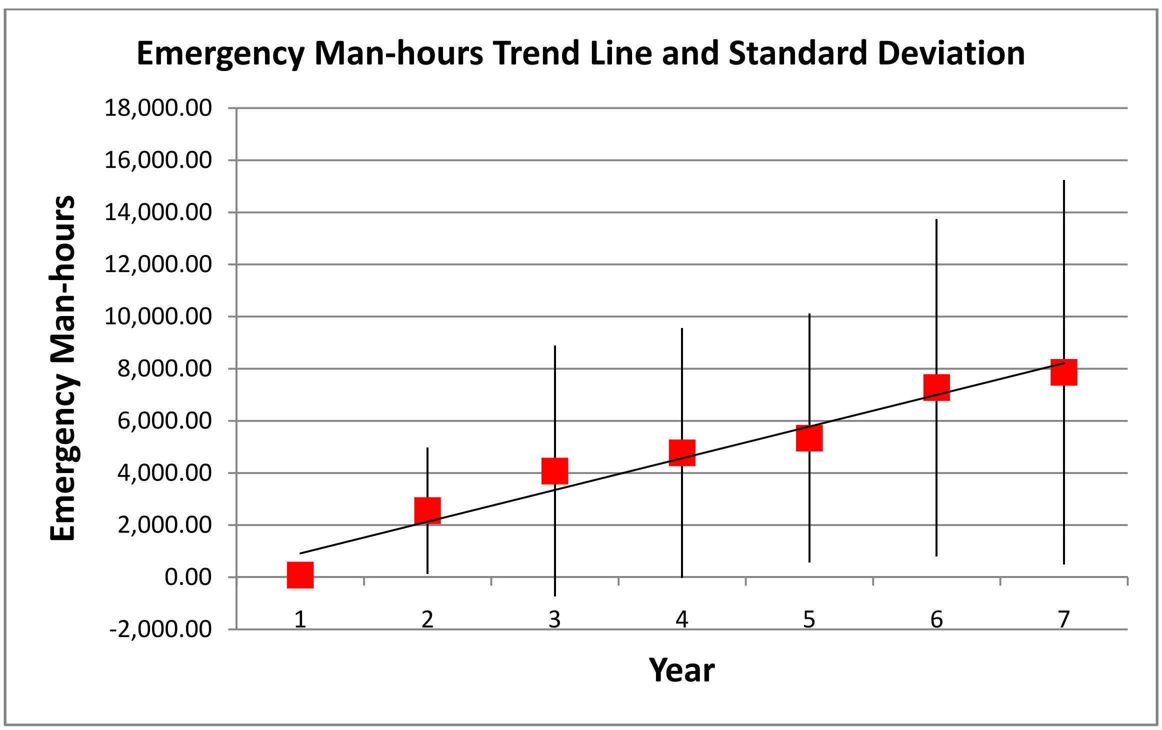

Figure 5a: Emergency Man-hours Trend Line and Standard Deviation, FY01-07

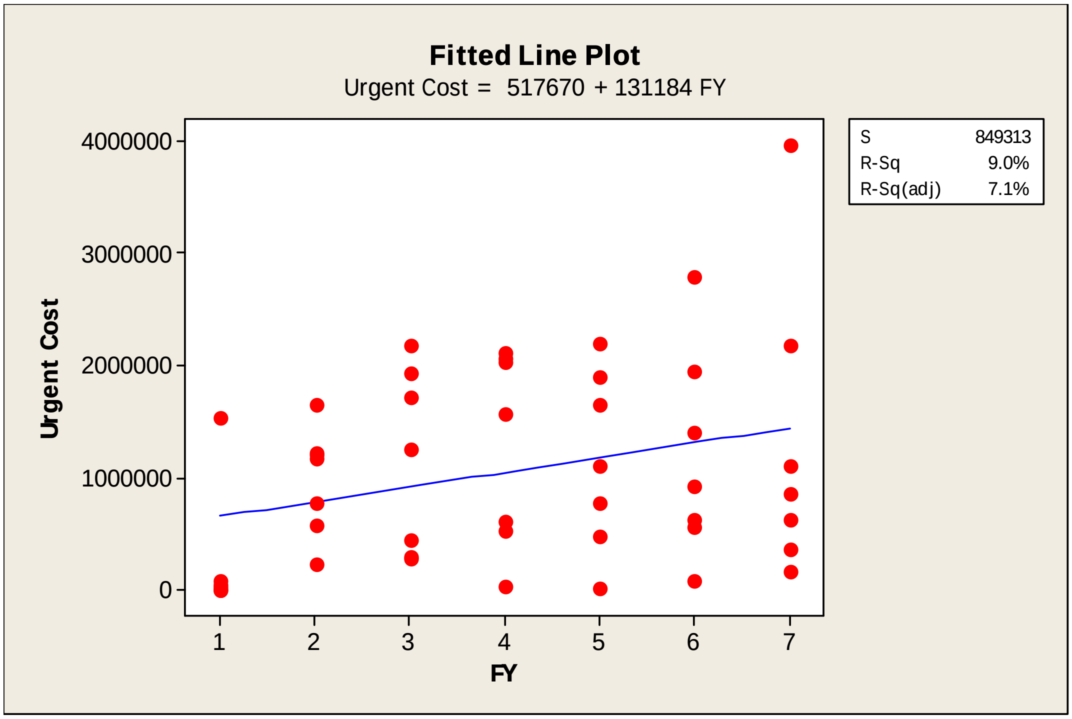

Figure 6: Urgent Costs Trend Line with Observations, FY01-07

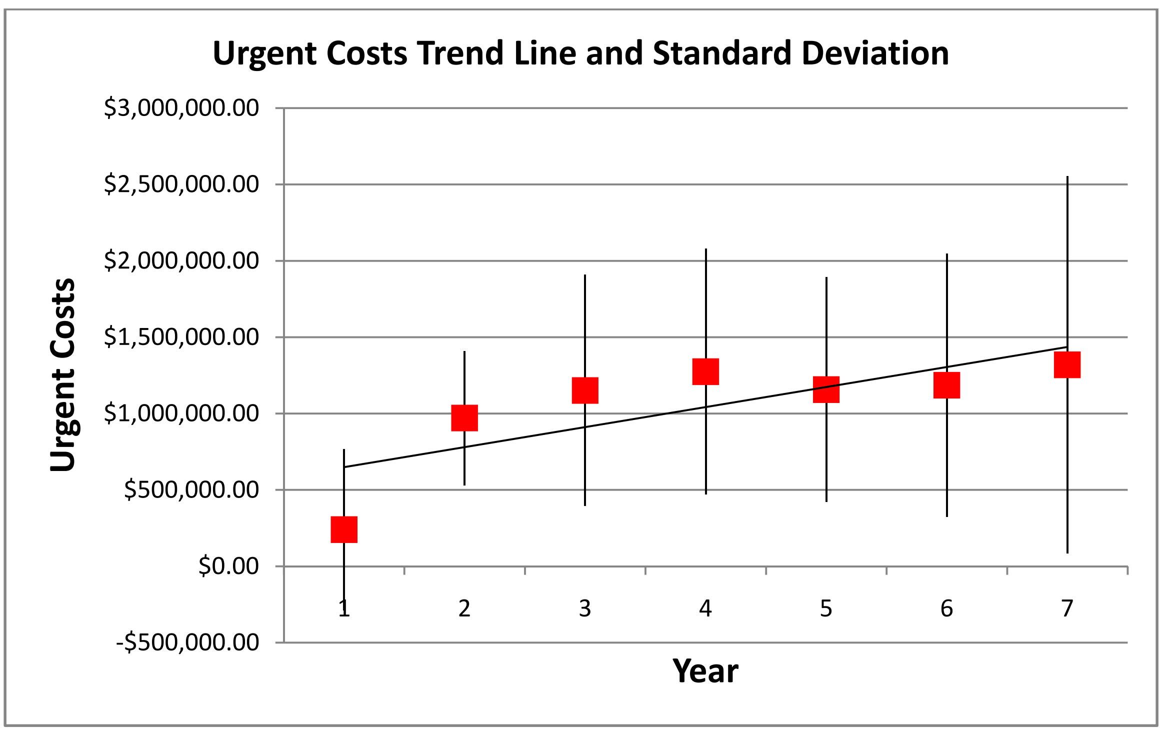

Figure 6a: Urgent Costs Trend Line and Standard Deviation, FY01-07

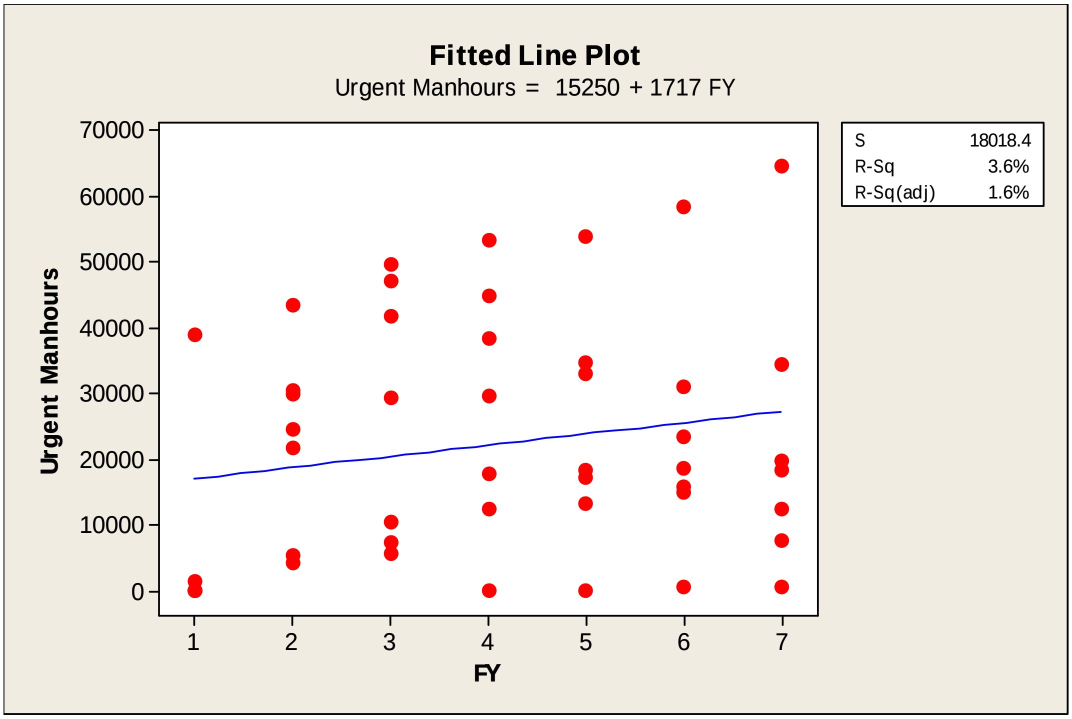

Figure 7: Urgent Man-hours Trend Line with Observations, FY01-07

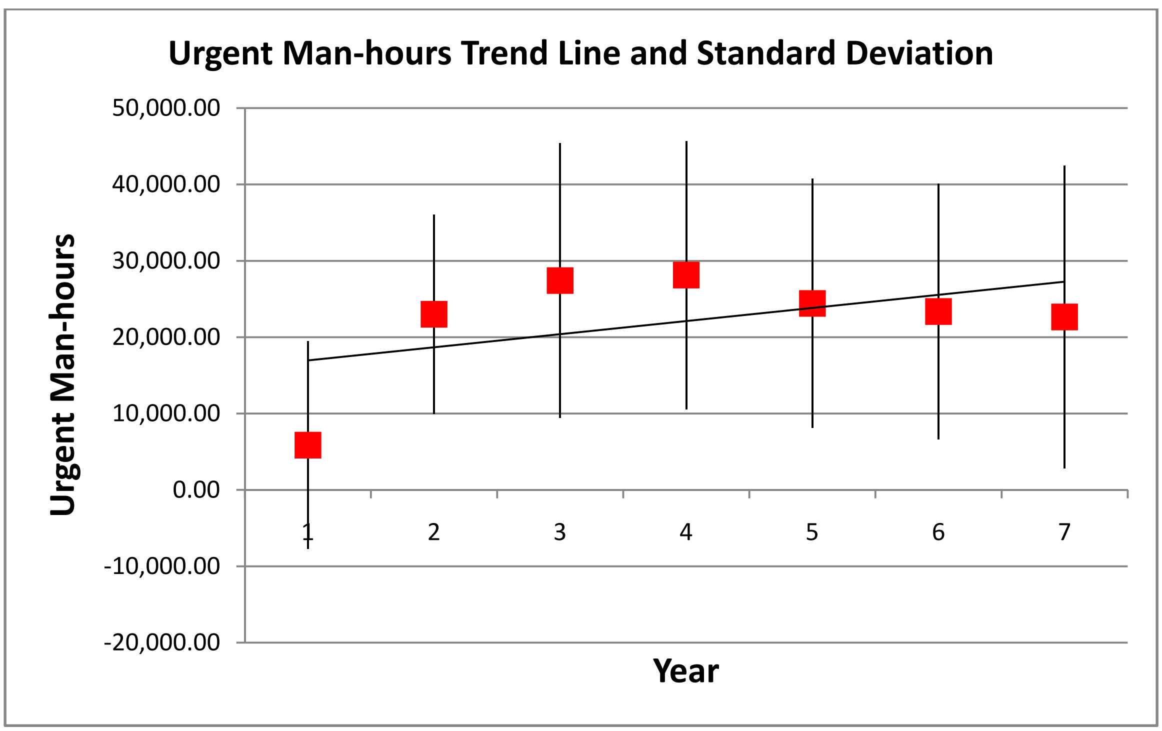

Figure 7a: Urgent Man-hours Trend Line and Standard Deviation, FY01-07

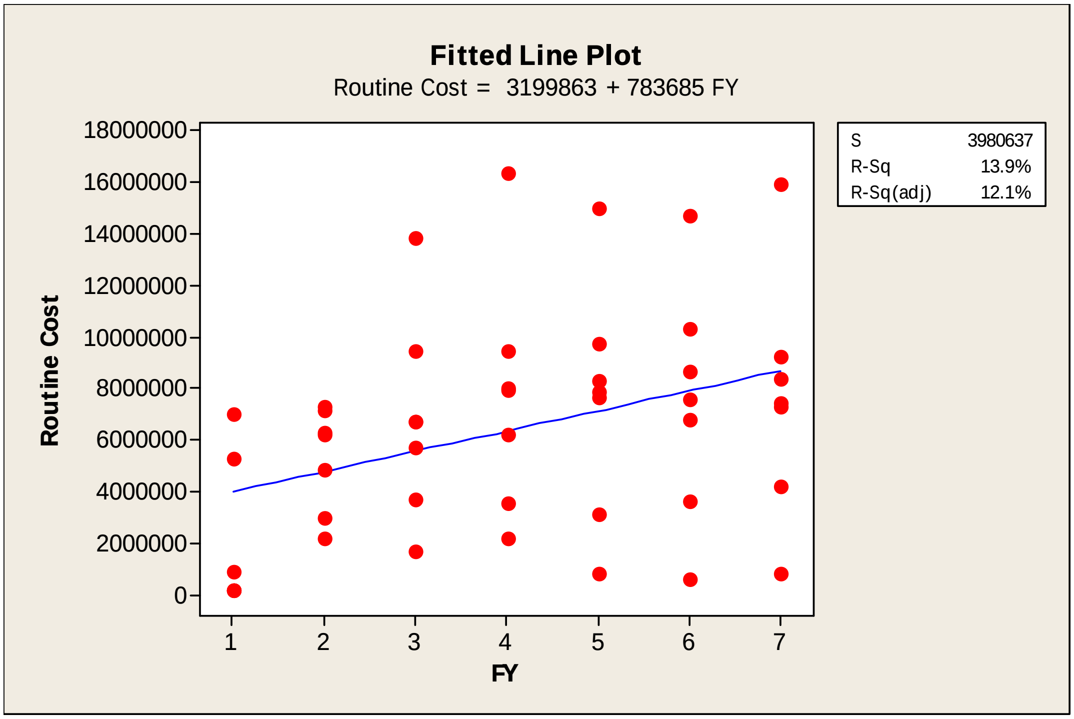

Figure 8: Routine Costs Trend Line with Observations, FY01-07

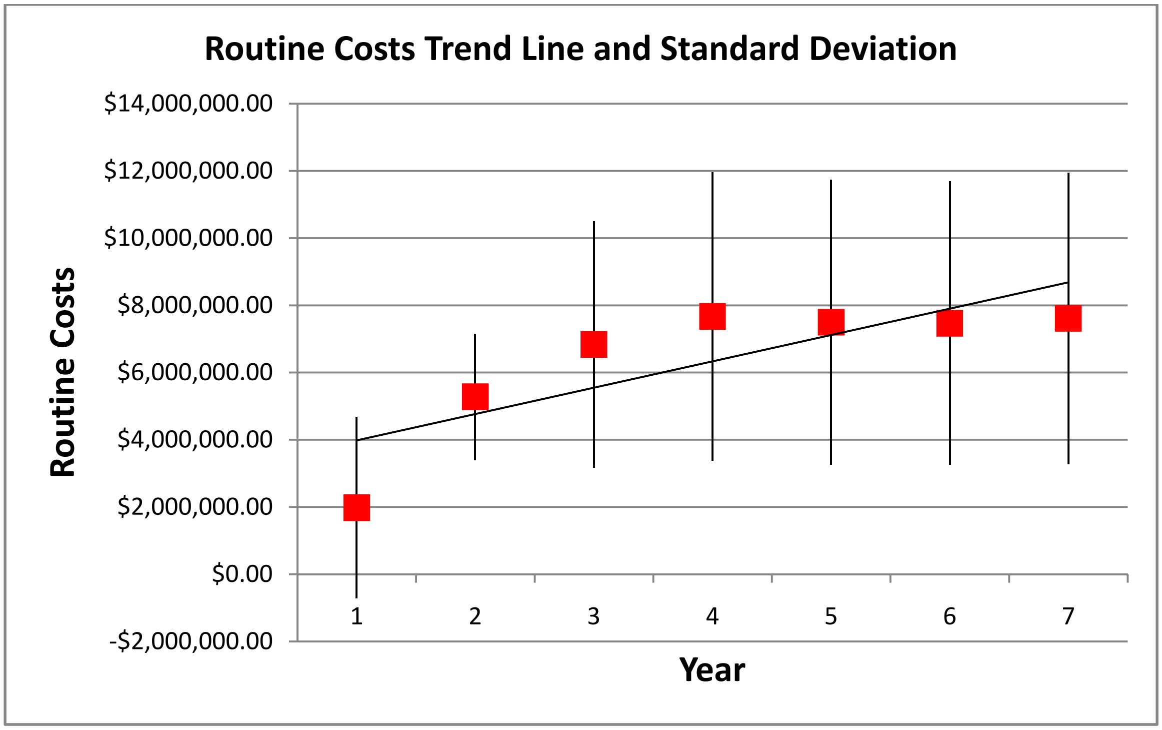

Figure 8a: Routine Costs Trend Line and Standard Deviation, FY01-07

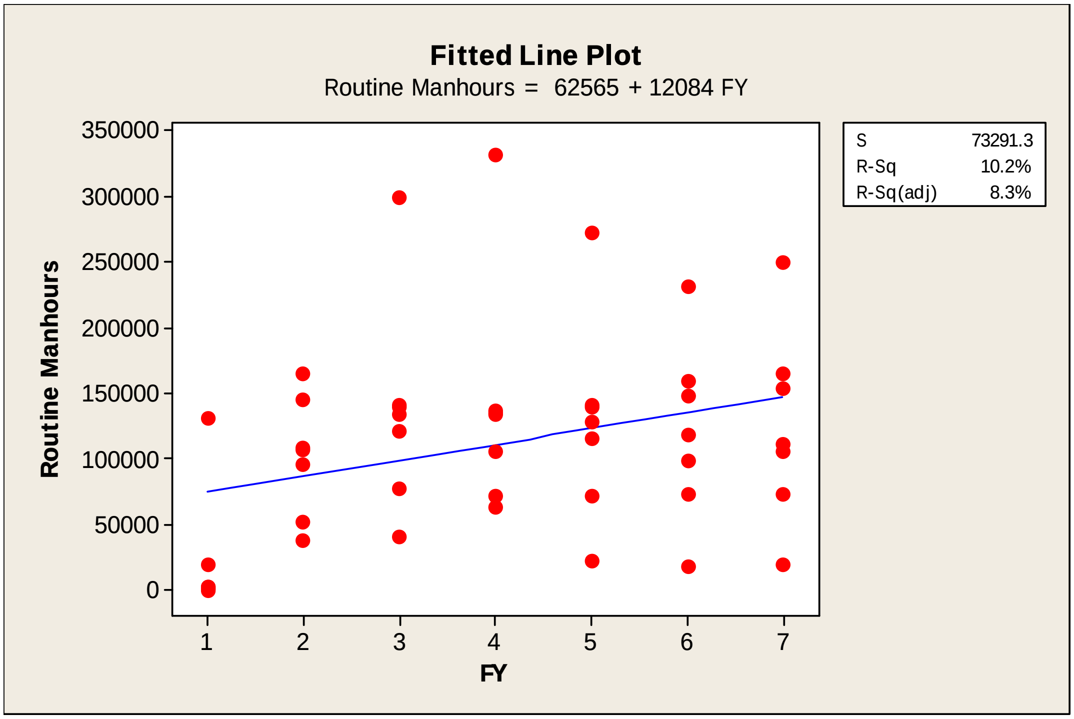

Figure 9: Routine Man-hours Trend Line with Observations, FY01-07

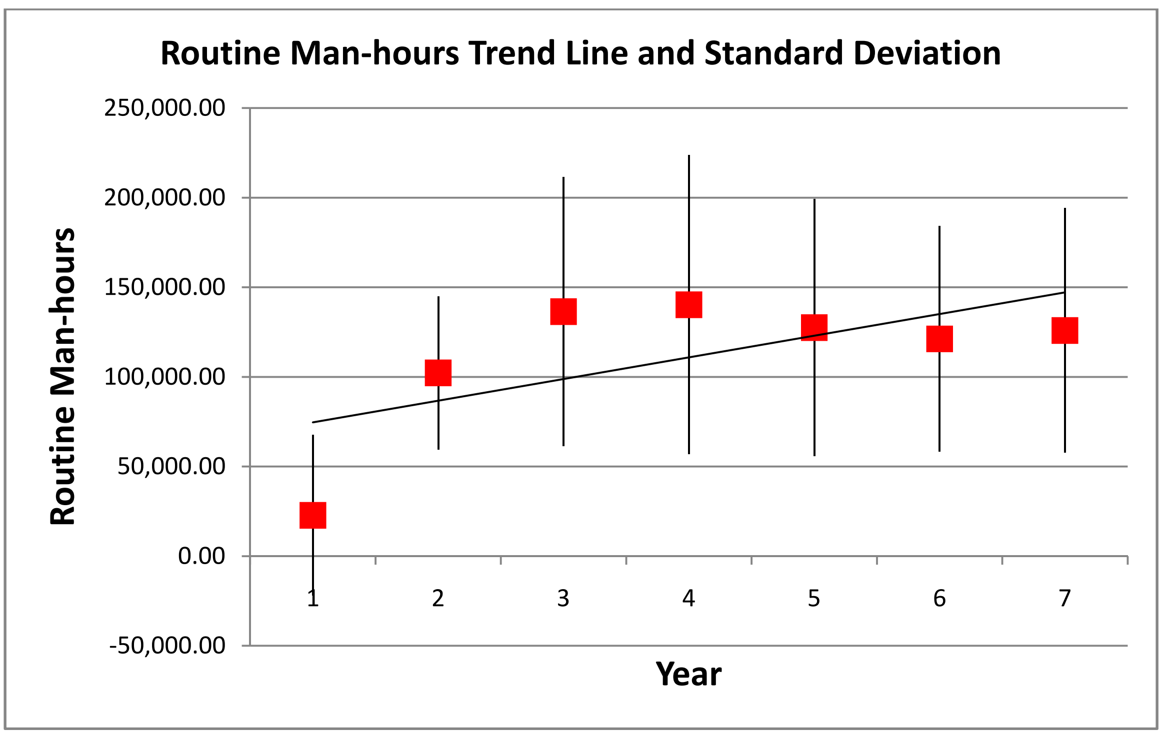

Figure 9a: Routine Man-hours Trend Line and Standard Deviation, FY01-07

Single Predictor Analysis

The following tables present the results of simple regression using each of the single predictors (leftmost column) anticipated to contribute most to the variability observed in each of the dependent variables (top row). In each case the p-value, R-squared, and adjusted R-squared are shown. Single predictors of significant impact upon the dependant variables (p-value less than 0.05) are called out with bold-underlined font.

This analysis was performed to determine whether there was a single predictor in any case that accounted for a very high amount of the variability in the various dependent variables with significance. In this way, we investigated whether there was a simple, single predictor model for any of the dependent variables across the range of one to five year lags. For example, a single predictor with an R-squared greater than 80% with an associated p-value less than 0.05 would be of great interest. As can be seen in Tables 1-5, the best case occurs with the predictor Total Executed upon the dependent variable Routine Cost with a one year lag, R-squared of 69.4%, and p-value of 0.000. While a single predictor with the extremely high level of explanatory power sought after was not found, valuable insight was discovered on the statistical characteristics and patterns of predictors repeatedly indicating either high or low levels of significance relative to one another. This information guided our continued analysis. For example, Sustainment and RWP routinely exhibited low R-squared and high p-values, with PRV and Modernization Executed exhibiting opposite attributes. The following tables summarize this information.

One Year Lag	Emergency Manhours			Emergency Cost		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.722	0.30%	0.00%	0.581	0.80%	0.00%
RWP	0.500	1.10%	0.00%	0.966	0.00%	0.00%
WOs	**0.000**	29.50%	27.70%	**0.001**	25.60%	23.70%
Sustainment	0.276	3.00%	0.50%	0.213	3.90%	1.40%
Restoration Executed	0.085	7.20%	4.90%	0.115	6.10%	3.70%
Modernization Executed	0.068	8.10%	5.80%	0.143	5.30%	2.90%
Total Executed	0.225	3.70%	1.20%	0.255	3.20%	0.80%
Requirement - Executed	**0.002**	20.90%	18.90%	**0.012**	14.90%	12.80%
	Urgent Manhours			**Urgent Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.014**	14.30%	12.10%	0.416	1.70%	0.00%
RWP	0.899	0.00%	0.00%	0.127	5.70%	3.40%
WOs	**0.011**	15.20%	13.00%	0.866	0.10%	0.00%
Sustainment	0.653	0.50%	0.00%	0.724	0.30%	0.00%
Restoration Executed	0.102	6.50%	4.20%	0.642	0.50%	0.00%
Modernization Executed	**0.038**	10.30%	8.10%	0.753	0.30%	0.00%
Total Executed	0.790	0.20%	0.00%	0.633	0.60%	0.00%
Requirement - Executed	**0.006**	17.60%	15.60%	0.455	1.40%	0.00%
	Routine Manhours			**Routine Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.000**	28.60%	26.80%	**0.000**	44.50%	43.10%
RWP	**0.007**	17.10%	15.00%	**0.015**	13.90%	11.70%
WOs	0.973	0.00%	0.00%	0.844	0.10%	0.00%
Sustainment	**0.009**	16.00%	13.90%	**0.003**	20.20%	18.20%
Restoration Executed	**0.001**	24.70%	22.80%	**0.000**	33.10%	31.40%
Modernization Executed	**0.000**	45.30%	44.00%	**0.000**	47.80%	46.50%
Total Executed	**0.000**	54.10%	52.90%	**0.000**	69.40%	68.60%
Requirement - Executed	0.610	0.70%	0.00%	0.727	0.30%	0.00%
	Total Manhours			**Total Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.000**	39.60%	38.00%	**0.009**	15.80%	13.70%
RWP	**0.009**	15.80%	13.70%	**0.013**	14.40%	12.20%
WOs	0.361	2.10%	0.00%	0.750	0.30%	0.00%
Sustainment	**0.008**	16.10%	14.00%	0.139	5.40%	3.00%
Restoration Executed	**0.007**	16.80%	14.70%	0.314	2.50%	0.10%
Modernization Executed	**0.000**	32.20%	30.50%	0.144	5.30%	2.90%
Total Executed	**0.000**	49.70%	48.40%	0.091	7.00%	4.70%
Requirement - Executed	0.709	0.40%	0.00%	0.429	1.60%	0.00%

Table 1: Single Predictor Regression Results (One Year Lag)

Two Year Lag	Emergency Manhours			Emergency Cost		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.920	0.00%	0.00%	0.734	0.40%	0.00%
RWP	0.337	2.80%	0.00%	0.821	0.20%	0.00%
WOs	**0.000**	35.30%	33.40%	**0.000**	39.80%	37.90%
Sustainment	0.257	3.90%	1.00%	0.203	4.90%	2.00%
Restoration Executed	0.078	9.10%	6.30%	0.095	8.20%	5.50%
Modernization Executed	**0.039**	12.20%	9.60%	0.062	10.20%	7.40%
Total Executed	0.240	4.20%	1.30%	0.271	3.70%	0.70%
Requirement - Executed	**0.014**	16.80%	14.30%	**0.026**	14.20%	11.60%
	Urgent Manhours			**Urgent Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.044**	11.80%	9.10%	**0.033**	13.00%	10.40%
RWP	0.352	2.60%	0.00%	0.822	20.00%	0.00%
WOs	**0.011**	17.90%	15.40%	**0.018**	15.70%	13.20%
Sustainment	0.759	0.30%	0.00%	0.860	0.10%	0.00%
Restoration Executed	0.193	5.10%	2.20%	0.234	4.30%	1.40%
Modernization Executed	**0.017**	16.20%	13.60%	**0.049**	11.30%	8.60%
Total Executed	0.604	0.80%	0.00%	0.758	0.30%	0.00%
Requirement - Executed	**0.002**	25.90%	23.60%	**0.015**	16.80%	14.30%
	Routine Manhours			**Routine Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.001**	30.70%	28.60%	**0.000**	47.00%	45.40%
RWP	**0.007**	20.20%	17.80%	**0.007**	20.20%	17.80%
WOs	0.884	0.10%	0.00%	0.832	0.10%	0.00%
Sustainment	**0.010**	18.30%	15.80%	**0.003**	23.60%	21.30%
Restoration Executed	**0.008**	19.30%	16.80%	**0.001**	27.30%	25.10%
Modernization Executed	**0.000**	40.40%	38.60%	**0.000**	43.00%	41.30%
Total Executed	**0.000**	48.80%	47.30%	**0.000**	64.40%	63.40%
Requirement - Executed	0.450	1.70%	0.00%	0.518	1.30%	0.00%
	Total Manhours			**Total Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.000**	42.80%	41.10%	**0.000**	57.60%	56.30%
RWP	**0.016**	16.50%	13.90%	**0.009**	18.90%	16.40%
WOs	0.459	1.70%	0.00%	0.360	2.50%	0.00%
Sustainment	**0.015**	16.70%	14.10%	**0.005**	21.30%	18.90%
Restoration Executed	**0.030**	13.60%	10.90%	**0.006**	20.80%	18.40%
Modernization Executed	**0.001**	27.20%	25.00%	**0.000**	31.10%	29.10%
Total Executed	**0.000**	45.70%	44.00%	**0.000**	59.50%	58.30%
Requirement - Executed	0.880	0.10%	0.00%	0.992	0.00%	0.00%

Table 2: Single Predictor Regression Results (Two Year Lag)

	Emergency Manhours			Emergency Cost		
Three Year Lag	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.809	0.20%	0.00%	0.929	0.00%	0.00%
RWP	0.257	4.90%	1.30%	0.744	0.40%	0.00%
WOs	**0.002**	31.40%	28.70%	**0.000**	47.00%	45.00%
Sustainment	0.314	3.90%	0.20%	0.288	4.30%	0.70%
Restoration Executed	0.098	10.10%	6.70%	0.055	13.40%	10.10%
Modernization Executed	**0.018**	19.70%	16.60%	**0.038**	15.50%	12.30%
Total Executed	0.358	3.30%	0.00%	0.317	3.80%	0.10%
Requirement - Executed	**0.041**	15.10%	11.80%	**0.022**	18.60%	15.40%
	Urgent Manhours			**Urgent Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.158	7.50%	4.00%	0.116	9.30%	5.80%
RWP	0.393	2.80%	0.00%	0.965	0.00%	0.00%
WOs	**0.010**	23.00%	20.00%	**0.004**	27.90%	25.10%
Sustainment	0.432	2.40%	0.00%	0.528	1.50%	0.00%
Restoration Executed	0.589	1.10%	0.00%	0.373	3.10%	0.00%
Modernization Executed	**0.010**	23.10%	20.20%	**0.029**	17.00%	13.80%
Total Executed	0.675	0.70%	0.00%	0.639	0.90%	0.00%
Requirement - Executed	**0.003**	29.80%	27.10%	**0.004**	27.60%	24.80%
	Routine Manhours			**Routine Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.002**	31.90%	29.30%	**0.000**	47.50%	45.50%
RWP	**0.011**	22.60%	19.60%	**0.007**	24.90%	22.00%
WOs	0.882	0.10%	0.00%	0.789	0.30%	0.00%
Sustainment	**0.011**	22.60%	19.60%	**0.004**	28.20%	25.40%
Restoration Executed	**0.029**	17.00%	13.80%	**0.014**	21.20%	18.10%
Modernization Executed	**0.000**	49.10%	47.20%	**0.000**	49.10%	47.10%
Total Executed	**0.000**	50.30%	48.40%	**0.000**	61.80%	60.40%
Requirement - Executed	0.352	3.30%	0.00%	0.420	2.50%	0.00%
	Total Manhours			**Total Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.000**	42.50%	40.30%	**0.000**	57.20%	55.50%
RWP	**0.022**	18.50%	15.40%	**0.008**	24.30%	21.40%
WOs	0.475	2.00%	0.00%	0.282	4.40%	0.80%
Sustainment	**0.020**	19.00%	15.90%	**0.008**	24.10%	21.20%
Restoration Executed	0.051	13.90%	10.60%	**0.035**	15.90%	12.70%
Modernization Executed	**0.002**	32.00%	29.40%	**0.001**	34.30%	31.80%
Total Executed	**0.000**	48.90%	46.90%	**0.000**	56.80%	55.10%
Requirement - Executed	0.935	0.00%	0.00%	0.931	0.00%	0.00%

Table 3: Single Predictor Regression Results (Three Year Lag)

	Emergency Manhours			Emergency Cost		
Four Year Lag	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.498	2.40%	0.00%	0.789	0.40%	0.00%
RWP	0.186	9.00%	4.20%	0.704	0.80%	0.00%
WOs	**0.044**	19.70%	15.40%	**0.004**	35.70%	32.30%
Sustainment	0.277	6.20%	1.30%	0.267	6.50%	1.50%
Restoration Executed	0.497	2.50%	0.00%	0.445	3.10%	0.00%
Modernization Executed	**0.010**	30.00%	26.30%	**0.020**	25.50%	21.50%
Total Executed	0.392	3.90%	0.00%	0.429	3.30%	0.00%
Requirement - Executed	0.313	5.30%	0.40%	0.098	13.70%	9.20%
	Urgent Manhours			**Urgent Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.326	5.10%	0.10%	0.276	6.20%	1.30%
RWP	0.580	1.60%	0.00%	0.749	0.60%	0.00%
WOs	**0.014**	27.60%	23.80%	**0.006**	33.10%	29.60%
Sustainment	0.232	7.40%	2.50%	0.274	6.30%	1.30%
Restoration Executed	0.655	1.10%	0.00%	0.889	0.10%	0.00%
Modernization Executed	**0.023**	24.50%	20.50%	0.409	18.90%	14.60%
Total Executed	0.756	0.50%	0.00%	0.731	0.60%	0.00%
Requirement - Executed	**0.009**	30.50%	26.90%	**0.003**	38.30%	35.10%
	Routine Manhours			**Routine Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.002**	41.20%	38.10%	**0.000**	51.80%	49.20%
RWP	**0.024**	24.20%	20.20%	**0.012**	28.60%	24.80%
WOs	0.964	0.00%	0.00%	0.719	0.70%	0.00%
Sustainment	**0.003**	37.60%	34.30%	**0.002**	39.50%	36.30%
Restoration Executed	0.189	8.90%	4.10%	0.204	8.30%	3.50%
Modernization Executed	**0.000**	49.90%	47.30%	**0.000**	48.20%	45.50%
Total Executed	**0.000**	55.10%	52.80%	**0.000**	58.00%	55.80%
Requirement - Executed	0.486	2.60%	0.00%	0.540	2.00%	0.00%
	Total Manhours			**Total Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.000**	49.80%	47.10%	**0.000**	59.40%	57.30%
RWP	**0.045**	19.60%	15.30%	**0.011**	29.70%	26.00%
WOs	0.397	3.80%	0.00%	0.267	6.40%	1.50%
Sustainment	**0.013**	28.40%	24.70%	**0.009**	30.60%	27.00%
Restoration Executed	0.158	10.20%	5.50%	0.212	8.10%	3.20%
Modernization Executed	**0.011**	29.20%	25.50%	**0.008**	31.50%	27.90%
Total Executed	**0.000**	52.60%	50.10%	**0.000**	53.30%	50.90%
Requirement - Executed	0.982	0.00%	0.00%	0.919	0.10%	0.00%

Table 4: Single Predictor Regression Results (Four Year Lag)

Five Year Lag	**Emergency Manhours**			**Emergency Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.472	4.40%	0.00%	0.751	0.90%	0.00%
RWP	0.096	21.30%	14.80%	0.325	8.10%	0.40%
WOs	0.131	18.00%	11.20%	**0.016**	39.50%	34.40%
Sustainment	0.325	8.10%	0.40%	0.297	9.00%	1.40%
Restoration Executed	0.688	1.40%	0.00%	0.612	2.20%	0.00%
Modernization Executed	**0.026**	35.00%	29.60%	**0.041**	30.50%	24.70%
Total Executed	0.372	6.70%	0.00%	0.412	5.70%	0.00%
Requirement - Executed	0.483	4.20%	0.00%	0.795	0.60%	0.00%
	Urgent Manhours			**Urgent Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	0.452	4.80%	0.00%	0.437	5.10%	0.00%
RWP	0.460	4.60%	0.00%	0.901	0.10%	0.00%
WOs	**0.020**	37.50%	32.30%	**0.007**	47.30%	42.90%
Sustainment	0.337	7.70%	0.00%	0.304	8.80%	1.20%
Restoration Executed	0.494	4.00%	0.00%	0.709	1.20%	0.00%
Modernization Executed	0.051	28.10%	22.10%	0.090	22.10%	15.60%
Total Executed	0.989	0.00%	0.00%	0.875	0.20%	0.00%
Requirement - Executed	0.250	10.90%	3.40%	0.173	14.90%	7.80%
	Routine Manhours			**Routine Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.011**	43.30%	38.50%	**0.005**	50.30%	46.10%
RWP	0.059	26.70%	20.50%	**0.027**	34.60%	29.20%
WOs	0.947	0.00%	0.00%	0.740	1.00%	0.00%
Sustainment	**0.023**	36.10%	30.80%	**0.018**	38.40%	33.30%
Restoration Executed	0.769	0.70%	0.00%	0.820	0.50%	0.00%
Modernization Executed	**0.013**	41.30%	36.40%	**0.010**	43.90%	39.20%
Total Executed	**0.002**	56.40%	52.80%	**0.001**	58.60%	55.10%
Requirement - Executed	0.926	0.10%	0.00%	0.965	0.00%	0.00%
	Total Manhours			**Total Cost**		
	P-Value	R-Sq	Adj R-Sq	P-Value	R-Sq	Adj R-Sq
PRV	**0.004**	51.20%	47.10%	**0.002**	57.60%	54.10%
RWP	0.137	17.50%	10.60%	**0.038**	31.20%	25.50%
WOs	0.405	5.80%	0.00%	0.272	10.00%	2.50%
Sustainment	0.064	25.70%	19.50%	0.055	27.40%	21.40%
Restoration Executed	0.651	1.80%	0.00%	0.776	0.70%	0.00%
Modernization Executed	0.112	19.70%	13.00%	0.066	25.50%	19.30%
Total Executed	**0.002**	55.40%	51.70%	**0.003**	54.30%	50.40%
Requirement - Executed	0.733	1.00%	0.00%	0.792	0.60%	0.00%

Table 5: Single Predictor Regression Results (Five Year Lag)

Correlation Analysis

The correlation analysis revealed two important points. First, by looking at the correlation coefficients and the p-values in conjunction with the single predictor regression performed earlier, we add to our confidence in identifying the predictors that may be most significant in the model. Tables 6-10 show the results for correlation analysis. The bold items under each dependent variable heading correspond with the predictors we used during our first run regression analysis. Not all of the bold predictors made it into the final model, but they provided a starting point.

Second, the correlation coefficient gave us some interesting insight into the relationship between that predictor and the specific outcomes. Specifically, we are interested to see whether certain predictors have negative or positive correlations with the different outcomes. At the start of this research, we expected to see negative correlations between infrastructure investments represented by the predictors Recurring Work Program, Work Orders, Sustainment, Restoration Executed, Modernization Executed, and Total Executed. In other words, we were expected higher investment would result in less unscheduled maintenance requirements. Further we expected to see a positive correlation between the Plant Replacement Value and the Requirement minus Executed predictors and the unscheduled maintenance variables. In other words, we expected that the larger the base and the greater the difference between funding requested and funding actually obligated would each result in higher unscheduled maintenance requirements. Looking at the Tables 6-10, the bolded items highlight the significant correlations.

One Year Lag Correlations	Emergency Manhours		Emergency Cost		Urgent Manhours		Urgent Cost	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	0.057	0.722	0.088	0.581	**0.378**	**0.014**	**0.385**	**0.012**
RWP	-0.107	0.500	0.007	0.966	-0.020	0.899	0.047	0.767
WOs	**0.543**	**0.000**	**0.506**	**0.001**	**0.389**	**0.011**	0.297	0.056
Sustainment	-0.172	0.276	-0.196	0.213	0.071	0.653	0.063	0.691
Restoration Executed	-0.269	0.085	-0.247	0.115	-0.256	0.102	-0.224	0.154
Modernization Executed	-0.284	0.068	-0.230	0.143	**-0.322**	**0.038**	-0.264	0.091
Total Executed	-0.191	0.225	-0.179	0.255	-0.042	0.790	-0.023	0.884
Requirement - Executed	**0.457**	**0.002**	**0.386**	**0.012**	**0.420**	**0.006**	0.292	0.061
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	2847.3	0.005	129671	0.004	6338	0.359	215688	0.578
PRV					0.00000592	0.005	0.0002819	0.012
RWP								
WOs	0.00024186	0.000	0.009594	0.001				
Sustainment								
Restoration Executed								
Modernization Executed					-0.002058	0.012		
Total Executed								
Requirement - Executed					0.0002848	0.046		
R-Squared	29.50%		25.60%		38.10%		14.80%	
Adjusted R-Squared	27.70%		23.70%		33.20%		12.70%	

	Routine Manhours		Routine Cost		Total Manhours		Total Cost	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	**0.535**	**0.000**	**0.667**	**0.000**	**0.629**	**0.000**	**0.734**	**0.000**
RWP	**0.413**	**0.007**	**0.372**	**0.015**	**0.397**	**0.009**	**0.373**	**0.015**
WOs	0.005	0.973	0.031	0.844	0.144	0.361	0.122	0.441
Sustainment	**0.400**	**0.009**	**0.449**	**0.003**	**0.401**	**0.008**	**0.439**	**0.004**
Restoration Executed	**0.497**	**0.001**	**0.575**	**0.000**	**0.409**	**0.007**	**0.499**	**0.001**
Modernization Executed	**0.673**	**0.000**	**0.691**	**0.000**	**0.567**	**0.000**	**0.604**	**0.000**
Total Executed	**0.735**	**0.000**	**0.833**	**0.000**	**0.705**	**0.000**	**0.796**	**0.000**
Requirement - Executed	-0.081	0.610	-0.055	0.727	0.059	0.709	0.030	0.853
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	-8887	0.644	-2425316	0.002	-14590	0.394	-1905207	0.017
PRV								
RWP	0.008679	0.002	0.5597	0.000	0.010606	0.000	0.565	0.000
WOs								
Sustainment					-0.004536	0.041	-0.2467	0.015
Restoration Executed	-0.006388	0.002	-0.2307	0.002	-0.009147	0.000	-0.48981	0.000
Modernization Executed	0.008638	0.040						
Total Executed	0.0037059	0.000	0.25685	0.000	0.0061178	0.000	0.36211	0.000
Requirement - Executed								
R-Squared	75.50%		84.70%		75.80%		85.40%	
Adjusted R-Squared	72.80%		83.40%		73.20%		83.80%	

Table 6: Correlations and Multiple Predictor Regression Results (One Year Lag)

Two Year Lag Correlations	**Emergency Manhours**		**Emergency Cost**		**Urgent Manhours**		**Urgent Cost**	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	0.018	0.920	0.060	0.734	**0.343**	**0.044**	**0.361**	**0.033**
RWP	-0.167	0.337	-0.040	0.821	-0.162	0.352	-0.039	0.822
WOs	**0.594**	**0.000**	**0.631**	**0.000**	**0.423**	**0.011**	**0.397**	**0.018**
Sustainment	-0.197	0.257	-0.220	0.203	-0.054	0.759	-0.031	0.860
Restoration Executed	-0.302	0.078	-0.287	0.095	-0.225	0.193	-0.206	0.234
Modernization Executed	**-0.350**	**0.039**	-0.319	0.062	**0.402**	**0.017**	**-0.336**	**0.049**
Total Executed	-0.204	0.240	-0.191	0.271	-0.091	0.604	-0.054	0.758
Requirement - Executed	**0.410**	**0.014**	**0.377**	**0.026**	**0.509**	**0.002**	**0.410**	**0.015**
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	3026	0.008	126198	0.007	7798	0.300	311074	0.460
PRV					0.00000535	0.018	0.0003392	0.007
RWP					-0.0022061	0.010		
WOs	0.00026772	0.000	0.012077	0.000	0.0003725	0.016		
Sustainment								
Restoration Executed								
Modernization Executed							-0.1203	0.010
Total Executed								
Requirement - Executed								
R-Squared	35.30%		39.80%		45.40%		29.60%	
Adjusted R-Squared	33.40%		37.90%		40.20%		25.20%	

	Routine Manhours		**Routine Cost**		**Total Manhours**		**Total Cost**	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	**0.554**	**0.001**	**0.685**	**0.000**	**0.654**	**0.000**	**0.759**	**0.000**
RWP	**0.450**	**0.007**	**0.450**	**0.007**	**0.406**	**0.016**	**0.434**	**0.009**
WOs	-0.026	0.884	0.037	0.832	0.129	0.459	0.159	0.360
Sustainment	**0.428**	**0.010**	**0.486**	**0.003**	**0.408**	**0.015**	**0.461**	**0.005**
Restoration Executed	**0.439**	**0.008**	**0.522**	**0.001**	**0.368**	**0.030**	**0.456**	**0.006**
Modernization Executed	**0.636**	**0.000**	**0.656**	**0.000**	**0.521**	**0.001**	**0.558**	**0.000**
Total Executed	**0.699**	**0.000**	**0.803**	**0.000**	**0.676**	**0.000**	**0.771**	**0.000**
Requirement - Executed	-0.132	0.450	-0.113	0.518	0.027	0.880	-0.002	0.992
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	-26836	0.202	-2451400	0.007	7746	0.710	-1063764	0.254
PRV								
RWP	0.012389	0.000	0.6939	0.000	0.01074	0.002	0.6743	0.000
WOs								
Sustainment								
Restoration Executed	-0.003826	0.048	-0.22033	0.007	-0.005369	0.007	-0.29828	0.001
Modernization Executed								
Total Executed	0.0040274	0.000	0.25581	0.000	0.0043653	0.000	0.27491	0.000
Requirement - Executed								
R-Squared	69.00%		84.10%		67.20%		81.60%	
Adjusted R-Squared	65.90%		82.50%		64.00%		79.80%	

Table 7: Correlations and Multiple Predictor Regression Results (Two Year Lag)

Three Year Lag Correlations	**Emergency Manhours**		**Emergency Cost**		**Urgent Manhours**		**Urgent Cost**	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	-0.048	0.809	0.018	0.929	0.274	0.158	0.304	0.116
RWP	-0.222	0.257	-0.065	0.744	-0.168	0.393	-0.009	0.965
WOs	**0.560**	**0.002**	**0.685**	**0.000**	**0.480**	**0.010**	**0.528**	**0.004**
Sustainment	-0.197	0.314	-0.208	0.288	-0.155	0.432	-0.124	0.528
Restoration Executed	-0.319	0.098	-0.366	0.055	-0.107	0.589	-0.175	0.373
Modernization Executed	**-0.444**	**0.018**	**-0.394**	**0.038**	**-0.481**	**0.010**	**-0.413**	**0.029**
Total Executed	-0.181	0.358	-0.196	0.317	-0.083	0.675	-0.093	0.639
Requirement - Executed	**0.388**	**0.041**	**0.431**	**0.022**	**0.546**	**0.003**	**0.525**	**0.004**
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	5910	0.000	220951	0.001	25416	0.000	1170669	0.000
PRV							.	
RWP								
WOs	0.000221	0.002	0.012119	0.000	0.0005362	0.011	0.0319	0.005
Sustainment								
Restoration Executed								
Modernization Executed	-0.0012535	0.017	-0.04498	0.026	-0.004119	0.011	-0.17774	0.033
Total Executed								
Requirement - Executed								
R-Squared	45.60%		56.70%		41.00%		40.10%	
Adjusted R-Squared	41.20%		53.20%		36.30%		35.30%	

	Routine Manhours		**Routine Cost**		**Total Manhours**		**Total Cost**	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	**0.565**	**0.002**	**0.689**	**0.000**	**0.652**	**0.000**	**0.756**	**0.000**
RWP	**0.475**	**0.011**	**0.499**	**0.007**	**0.431**	**0.022**	**0.493**	**0.008**
WOs	-0.029	0.882	0.053	0.789	0.141	0.475	0.211	0.282
Sustainment	**0.475**	**0.011**	**0.531**	**0.004**	**0.436**	**0.020**	**0.491**	**0.008**
Restoration Executed	**0.413**	**0.029**	**0.460**	**0.014**	0.373	0.051	**0.399**	**0.035**
Modernization Executed	**0.701**	**0.000**	**0.701**	**0.000**	**0.566**	**0.002**	**0.586**	**0.001**
Total Executed	**0.709**	**0.000**	**0.786**	**0.000**	**0.699**	**0.000**	**0.754**	**0.000**
Requirement - Executed	-0.183	0.352	-0.159	0.420	-0.016	0.935	-0.017	0.931
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	-36046	0.145	-3095681	0.008	6035	0.810	-1209412	0.334
PRV								
RWP	0.013199	0.001	0.814	0.000	0.011415	0.004	0.8073	0.000
WOs								
Sustainment								
Restoration Executed								
Modernization Executed								
Total Executed	0.0035708	0.000	0.23432	0.000	0.0034045	0.000	0.22436	0.000
Requirement - Executed								
R-Squared	68.50%		81.70%		63.60%		76.40%	
Adjusted R-Squared	66.00%		80.30%		60.60%		74.50%	

Table 8: Correlations and Multiple Predictor Regression Results (Three Year Lag)

Four Year Lag Correlations	**Emergency Manhours**		**Emergency Cost**		**Urgent Manhours**		**Urgent Cost**	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	-0.156	0.498	-0.062	0.789	0.226	0.326	0.249	0.276
RWP	-0.300	0.186	-0.088	0.704	-0.128	0.580	0.074	0.749
WOs	**0.444**	**0.044**	**0.597**	**0.004**	**0.525**	**0.014**	**0.575**	**0.006**
Sustainment	-0.249	0.277	-0.254	0.267	-0.272	0.232	-0.250	0.274
Restoration Executed	-0.157	0.497	-0.176	0.445	0.104	0.655	0.033	0.889
Modernization Executed	**-0.548**	**0.010**	**-0.505**	**0.020**	**-0.494**	**0.023**	**-0.434**	**0.049**
Total Executed	-0.197	0.392	-0.182	0.429	-0.072	0.756	-0.080	0.731
Requirement - Executed	0.231	0.313	0.371	0.098	**0.552**	**0.009**	**0.619**	**0.003**
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	9976	0.000	309606	0.000	16203	0.001	774172	0.002
PRV								
RWP								
WOs			0.011136	0.003				
Sustainment								
Restoration Executed								
Modernization Executed	-0.0019137	0.010	-0.06803	0.013				
Total Executed								
Requirement - Executed					0.000576	0.009	0.03537	0.003
R-Squared	30.00%		54.80%		30.50%		38.30%	
Adjusted R-Squared	26.30%		49.80%		26.90%		35.10%	

	Routine Manhours		**Routine Cost**		**Total Manhours**		**Total Cost**	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	**0.642**	**0.002**	**0.720**	**0.000**	**0.705**	**0.000**	**0.771**	**0.000**
RWP	**0.492**	**0.024**	**0.535**	**0.012**	**0.442**	**0.045**	**0.545**	**0.011**
WOs	0.011	0.964	0.083	0.719	0.195	0.397	0.254	0.267
Sustainment	**0.613**	**0.003**	**0.628**	**0.002**	**0.533**	**0.013**	**0.554**	**0.009**
Restoration Executed	0.298	0.189	0.289	0.204	0.319	0.158	0.284	0.212
Modernization Executed	**0.707**	**0.000**	**0.694**	**0.000**	**0.541**	**0.011**	**0.561**	**0.008**
Total Executed	**0.742**	**0.000**	**0.762**	**0.000**	**0.725**	**0.000**	**0.730**	**0.000**
Requirement - Executed	-0.161	0.486	-0.142	0.540	0.005	0.982	0.024	0.919
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	-13433	0.599	-3239480	0.013	11390	0.695	-1446323	0.282
PRV	0.00002996	0.001			0.00003516	0.000		
RWP			0.9622	0.000			0.9848	0.000
WOs								
Sustainment								
Restoration Executed								
Modernization Executed	0.022002	0.000			0.014574	0.011		
Total Executed			0.22796	0.000			0.21861	0.000
Requirement - Executed								
R-Squared	74.70%		84.30%		65.30%		80.70%	
Adjusted R-Squared	71.90%		82.50%		61.50%		78.60%	

Table 9: Correlations and Multiple Predictor Regression Results (Four Year Lag)

Five Year Lag Correlations	Emergency Manhours		Emergency Cost		Urgent Manhours		Urgent Cost	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	-0.209	0.472	-0.093	0.751	0.219	0.452	0.226	0.437
RWP	-0.462	0.096	-0.284	0.325	-0.215	0.460	-0.037	0.901
WOs	0.424	0.131	**0.628**	**0.016**	**0.613**	**0.020**	**0.688**	**0.007**
Sustainment	-0.284	0.325	-0.300	0.297	-0.277	0.337	-0.296	0.304
Restoration Executed	-0.118	0.688	-0.149	0.612	0.199	0.494	0.110	0.709
Modernization Executed	**-0.592**	**0.026**	**-0.552**	**0.041**	**-0.530**	**0.051**	-0.470	0.090
Total Executed	-0.259	0.372	-0.238	0.412	0.004	0.989	-0.046	0.875
Requirement - Executed	-0.204	0.483	-0.076	0.795	0.330	0.250	0.386	0.173
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	11714	0.000	376146	0.003	24072	0.002	724196	0.022
PRV								
RWP								
WOs			0.01488	0.014	0.0008498	0.020	0.06252	0.007
Sustainment								
Restoration Executed								
Modernization Executed	-0.002823	0.026	-0.10062	0.033	-0.00562	0.048		
Total Executed								
Requirement - Executed								
R-Squared	35.00%		60.70%		56.90%		47.30%	
Adjusted R-Squared	29.60%		53.60%		49.10%		42.90%	

	Routine Manhours		Routine Cost		Total Manhours		Total Cost	
	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value	Correlation	P-Value
PRV	**0.658**	**0.011**	**0.709**	**0.005**	**0.715**	**0.004**	**0.759**	**0.002**
RWP	0.516	0.059	**0.589**	**0.027**	0.418	0.137	**0.559**	**0.038**
WOs	0.020	0.947	0.098	0.740	0.242	0.405	0.316	0.272
Sustainment	**0.601**	**0.023**	**0.620**	**0.018**	0.507	0.064	0.524	0.055
Restoration Executed	0.086	0.769	0.067	0.820	0.133	0.651	0.084	0.776
Modernization Executed	**0.642**	**0.013**	**0.663**	**0.010**	0.444	0.112	0.505	0.066
Total Executed	**0.751**	**0.002**	**0.765**	**0.001**	**0.744**	**0.002**	**0.737**	**0.003**
Requirement - Executed	0.027	0.926	-0.013	0.965	0.100	0.733	0.078	0.792
Regression	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Constant	-12112	0.739	-4175151	0.009	20393	0.589	-2089276	0.253
PRV	0.00002997	0.013						
RWP			0.9997	0.000			0.948	0.002
WOs								
Sustainment								
Restoration Executed								
Modernization Executed	0.022854	0.016						
Total Executed			0.27875	0.000	0.004197	0.002	0.2683	0.000
Requirement - Executed								
R-Squared	67.20%		89.40%		55.40%		82.00%	
Adjusted R-Squared	61.20%		87.40%		51.70%		78.70%	

Table 10: Correlations and Multiple Predictor Regression Results (Five Year Lag)

Table 11 provides a summary of the significant predictors compared to the original expectations. As is evident by the table, there are few correlations with p-values below .05 that match the expectations described above. There are three general observations we can make based on the significant correlations. First, plant replacement value tends to only be significantly positively correlated with routine man-hours and costs and total man-hours and costs. Second, requirement minus obligations tends to be significantly positively correlated with emergency and urgent man-hours and costs.

Third, modernization executed tends to be significantly negatively correlated with emergency and urgent man-hours.

	Correlation Expectation	Number of Occasions	Possible Occasions
One Year Lag	Negative	1	48
	Positive	8	16
Two Year Lag	Negative	2	48
	Positive	10	16
Three Year Lag	Negative	4	48
	Positive	8	16
Four Year Lag	Negative	4	48
	Positive	6	16
Five Year Lag	Negative	3	48
	Positive	4	16

Table 11: Summary of Correlation Expectations

Overall, there are two conclusions we surmise from the correlation analysis. First, there were very few significant positive or negative correlations that aligned with our initial expectations. To better understand this circumstance, it may be necessary to obtain more detail on each predictor. We expected a significant negative correlation between the six infrastructure investment predictors and the eight different outcomes. This was only true in a few cases. If we had information on what kinds of projects were funded with those investment dollars we might better be able to understand the correlations. As a possible explanation, if a base invests work order funding on installing carpet, that investment would not help reduce the growing number of heating, ventilation, and air conditioning system emergency calls. With more information on the type of work being performed, we could better revise our expectations and/or better explain the correlations.

Second, the correlations appear to be consistent with the overall trends shown in the trend plots. And, as we will discuss below, the correlations foreshadow the results of our final model forecasting increasing man-hour and cost requirements.

In evaluating these correlations, we were careful not to make judgments on causal relationships. Instead this analysis is probably more useful as defining follow on research possibilities. Thoughts on follow on research as a result of this correlation analysis are provided below.

Regression

Referring back to our problem statement, the primary goal for this research was to develop a predictive model for forecasting future unscheduled maintenance requirements. To develop this model we use regression. As a starting point for our model building, we used only the significant predictors as identified by our correlation analysis described above. Referring back to Tables 6-10, the significant predictors are those predictors identified by p-values below .05 and highlighted in bold font. With the significant predictors as a starting point we ran consecutive models eliminating predictors with p-values above .05 after each step. The final models for each time lag and for each dependent variable are shown in Tables 6-10.

Looking at the various models, there are several observations. First, for each time lag we notice different ranges of R-Square Values. The ranges are summarized in Table 12. In general we see higher R-Square values for routine work and the totals. We also see higher R-square values for the longer lags. However, it is important to note that this may be mainly due to the lower number of observations.

	Number of Observations	Emergency Man-hours	Emergency Cost	Urgent Man-hours	Urgent Cost	Routine Man-hours	Routine Costs	Total Man-hours	Total Costs
One Year Lag	**42**	**27.7**	**23.7**	**33.2**	**12.7**	**72.8**	**83.4**	**73.2**	**83.8**
Two Year Lag	**35**	**33.4**	**37.9**	**40.2**	**25.2**	**65.9**	**82.5**	**64.0**	**79.8**
Three Year Lag	**28**	**41.2**	**53.2**	**36.3**	**35.3**	**66.0**	**80.3**	**60.6**	**74.5**
Four Year Lag	**21**	**26.3**	**49.8**	**26.9**	**35.1**	**71.9**	**82.5**	**61.5**	**78.6**
Five Year Lag	**14**	**29.6**	**53.6**	**49.1**	**42.9**	**61.2**	**87.4**	**51.7**	**78.7**

Table 12: Summary of R-Squared Values Range

Second, even though for each time lag we are able to achieve at least a few high R-Squares, there were not many models that shared consistent significant predictors for all dependent variables. The one exception to this is the three year lag data which shows decent models using consistent significant predictors. For emergency and urgent work, the consistent predictors are work orders and modernization executed. For routine work and the totals, the consistent predictors are RWP and Total Executed. As a result, we felt this three year lag model would be the easiest to use operationally and decided to analyze this model further accounting for time series data.

Given the R-Square values and the consistency of the predictors, the three year lag offers a final model for future forecasting. The final models are show below:

Emergency Man-hours = 5910 + .000221*Work Orders - .0012535*Modernization Executed

Emergency Costs = 220951 + .012119*Work Orders - .04498*Modernization Executed

Urgent Man-hours = 25416 + .0005362*Work Orders - .004119*Modernization Executed

Urgent Costs = 1170669 + .0319*Work Orders - .17774*Modernization Executed

Routine Man-hours = -36046 + .013199*RWP + .0035708*Total Executed

Routine Costs = -3095681 + .814*RWP + .23432*Total Executed

Total Man-hours = -6035 + .011415*RWP + .0034045*Total Executed

Total Costs = -1209412 + .8073*RWP + .22436*Total Executed

But, while this model will provide a good long term trend model, for more accuracy, it is important to evaluate the model to account for time series data. This process and the results are described below.

Autoregressive Model

Time series data is data generated by processes over time. While it is acceptable to forecast time series data using regression, there are two problems researchers need to be aware of. As with any forecast, we use known data to project into the future, if the underlying condition of the forecast changes drastically after the model is estimated, the forecasts could be useless. Also, regression with time series data "may adequately describe the long term trend, the model doesn't include any cyclical effects into the model. Thus, the effect of inflationary and recessionary periods will be to increase the error of the forecasts because the model does not anticipate such periods." (18)

Our time series data also qualifies as panel data because we have multiple independent variables for each year group. As such, we had to use variation of the Durbin Watson test, the Durbin Watson for Panel Data, as described in (19). The results show a positive autocorrelation signifying there is some trend in the errors for which our predictors have not accounted. Without some further time series analysis, the model would consistently be inaccurate. Therefore, we transformed the data using the procedure described in (18) and reran the regression analysis.

The revised models are:

Emergency Man-hours = No Model

Emergency Costs = 375402 + .011247*Work Orders-.05198*Modernization Executed

Urgent Man-hours = No Model

Urgent Costs = 1843651 - .17132*Modernization Executed + .031461*Requirement - Executed

Routine Man-hours = -10378 + .00003679*PRV + .008198*Modernization Executed

Routine Costs = -1618996 + .0022385*PRV + 1.0685*Modernization Executed

Total Man-hours = 1761 + .00004192*PRV

Total Costs = -580809 + .0025738*PRV + .6759*Modernization Executed

For these final models, we checked for correlation between the predictors using the Pearson Correlation Coefficients and the related P-Values. We found no correlation between the significant predictors. The results are listed below.

Dependent Variable	Significant Predictors	Pearson Value	P-Value
Emergency MH	None	-	-
Emergency Cost	Work Orders Modernization Executed	-.178	.441
Urgent MH	None	-	-
Urgent Cost	Modernization Executed Requirement – Executed	-.224	.328
Routine MH	PRV Modernization Executed	.190	.409
Routine Cost	PRV Modernization Executed	.221	.335
Total MH	PRV	-	-
Total Cost	PRV Modernization Executed	.208	.367

Table 13: Correlation between Predictors

We were able to develop models for six of the eight outcomes. It perhaps is not surprising that we were unable to develop models for Emergency Man-hours and Urgent Man-hours. One problem with these two outcomes is they make up only a very small subset of our overall data. From an operational perspective, this result is not surprising. Emergency and Urgent work is often caused by weather or other unpredictable events, such as a contractor hitting an electrical cable. In these cases no amount of investment will reduce the amount of man-hours required. Also, when dealing with infrastructure systems, often times they fail despite all the best preventative maintenance and investment routines. For these reasons, we were not surprised there were no significant models discovered.

The remaining models included four significant predictors: Work Orders, Modernization Executed, Requirement – Executed, and PRV. Work Orders is a positive significant predictor for Emergency Costs. While our expectation was that Work Orders should have a negative correlation, without knowing the nature of the work conducted under the Work Order investment, we have to be careful what we infer from our result. Work Orders are used for a variety of work. Some kinds of work, like replacing an aging pump, you might expect to reduce future unscheduled maintenance. On the other hand, a Work Order used to install carpet or paint rooms may not significantly reduce unscheduled maintenance. Given this nature of Work Order investment, without further detail, it is difficult to fully analyze this predictor.

Modernization Executed was significant in five of the six models. It is important to note that it is negatively correlated in emergency and urgent costs and positively correlated with Routine Man-hours, Routine Costs, and Total Costs. Modernization projects serve one of two functions. One, they may improve the existing infrastructure by bringing it up to a current standard. Or, two, they may install new equipment. Given these two different types of projects, there are some possible explanations for the negative and positive correlations. One possible explanation for the negative correlation might be the bases are upgrading the systems that are causing the most problems and, as a result, they are reducing the cost incurred for Emergency and Urgent work requirements. An explanation for the positive correlation for the Routine and Total categories, might be the installation of equipment is actually causing new failure points that increase the unscheduled maintenance. To be sure, more detail on the nature of the projects is needed.

Requirement – Executed was significant only in the model for Urgent Costs. This predictor represents the funding shortfall and is in line with our expectations that a larger shortfall results in more unscheduled maintenance. It is interesting this particular predictor only appeared in one model.

PRV was significant is four of the six models. It is not surprising that it is positive correlated in each case. This is in line with our expectations that the larger the PRV the more unscheduled maintenance.

As we offer this analysis using the final models and our own experience, we must also state that we must be careful inferring causality between the predictors and dependent variables. In each case, more details on the predictors are necessary to confirm or refute the analysis.

V. Discussion

Answers to Research Questions

Research Question 1: Can infrastructure failures (as represented by unscheduled maintenance and cost requirements) be forecasted as a function of the preceding level of Operations and Maintenance (O&M) funding invested?

Overall, the models do provide a quantitative method for forecasting future infrastructure failures. However, there are two observations we must discuss. First, with Adjusted R-Square values ranging from 12.7% to 87.4%, we are able to explain varying degrees of the variability. In general, the selected predictors account for more of the variability for routine man-hours and costs and total man-hours and costs than they do for emergency and urgent man-hours and costs. Second, there is a generally lack of consistency in predictors from outcome to outcome within a specific lag time. The one exception to this is the three year lag which can be fit into two models using just two sets of predictors. One set is useful for emergency and urgent work and the other is useful for routine and total work.

Research Question 2: What predictors are most significant?

Table 13 below summarizes the significant predictors for each model and the resultant R-Square values. Note Work Orders and Modernization Executed are the most often occurring predictors of emergency and routine work. The three year demonstrates this most consistently across all four variables for emergency and routine work. Even though they are significant and consistent, however, it should also be noted even in the three year models, Work Orders and Modernization account for only 35 to 53% of the total variability. For Routine and Total work, RWP, Restoration Executed, and Total Executed are the most common significant predictors, especially with one, two and three year lag.

Lag	Emergency Man-hours	Emergency Cost	Urgent Man-hours	Urgent Cost	Routine Man-hours	Routine Costs	Total Man-hours	Total Costs
1 Year Lag								
PRV			X	X				
RWP					X	X	X	X
WOs	X	X						
Sustainment							X	X
Rest Exec					X	X	X	X
Mod Exec			X		X			
Total Exec					X	X	X	X
Rqmt-Exec			X					
Adj R-Square	27.7	23.7	33.2	12.7	72.8	83.4	73.2	83.8
2 Year Lag								
PRV			X	X				
RWP			X		X	X	X	X
WOs	X	X	X					
Sustainment								
Rest Exec					X	X	X	X
Mod Exec				X				
Total Exec					X	X	X	X
Rqmt-Exec								
Adj R-Square	33.4	37.9	40.2	25.2	65.9	82.5	64.0	79.8
3 Year Lag								
PRV								
RWP					X	X	X	X
WOs	X	X	X	X				
Sustainment								
Rest Exec								
Mod Exec	X	X	X	X				
Total Exec					X	X	X	X
Rqmt-Exec								
Adj R-Square	41.2	53.2	36.3	35.3	66.0	80.3	60.6	74.5
4 Year Lag								

PRV					**X**		**X**	
RWP						**X**		**X**
WOs		**X**						
Sustainment								
Rest Exec								
Mod Exec	**X**	**X**			**X**		**X**	
Total Exec						**X**		**X**
Rqmt-Exec			**X**	**X**				
Adj R-Square	**26.3**	**49.8**	**26.9**	**35.10**	**71.9**	**82.5**	**61.5**	**78.6**
5 Year Lag								
PRV					**X**			
RWP						**X**		**X**
WOs		**X**	**X**	**X**				
Sustainment								
Rest Exec								
Mod Exec	**X**	**X**	**X**		**X**			
Total Exec						**X**	**X**	**X**
Rqmt-Exec								
Adj R-Square	**29.6**	**53.6**	**49.1**	**42.9**	**61.2**	**87.4**	**51.7**	**78.7**

Table 14: Summary of Significant Predictors for Long Term Trends

After transforming the data to account for time series the model changes as shown above. The significant predictors in the revised model are show in Table 14 below.

3 Year Lag Adjusted Time Series Model								
	Emergency Man-hours	**Emergency Cost**	**Urgent Man-hours**	**Urgent Cost**	**Routine Man-hours**	**Routine Costs**	**Total Man-hours**	**Total Costs**
PRV					**X**	**X**	**X**	**X**
RWP								
WOs		**X**						
Sustainment	**No Model**		**No Model**					
Rest Exec								
Mod Exec		**X**		**X**	**X**	**X**		**X**
Total Exec								
Rqmt-Exec				**X**				
Adj R-Square	**-**	**59.6**	**-**	**49.0**	**53.0**	**77.1**	**47.0**	**67.5**

Table 15: Summary of Significant Predictors of the Time Series Model

Research Question 3: Can the model help predict future infrastructure condition?

The model can be used to describe overall trends and forecast man-hour and cost requirements for unscheduled maintenance. However, the model alone should not be used to make judgments on future infrastructure conditions. Certainly, poor infrastructure condition will be contribute to an increase in costs and man-hour requirements for unscheduled maintenance, but without more detail on the investment predictors and the Emergency, Urgent and Routine work, it is difficult to say to what degree.

Relevance of Research

Civil Engineers continuously look for ways to justify additional funding to prevent the generally held belief of ever-increasing infrastructure requirements. The results of this research support this generally accepted view by demonstrating the current trends in man-hour and costs, evaluating the correlations between the various investment categories, and developing an over predictive model that forecasts a continued rising trend. Perhaps more importantly than just this overall trend, this study raises some interesting questions that civil engineer leaders should consider.

1) If we aren't experiencing negative correlations with our investment categories, are we effectively spending infrastructure dollars? While it may be the case that the civil engineer community simply doesn't have enough funds and no matter what is done the infrastructure demands will continue to rise, it still is important to ensure we are spending limited dollars we do have on the most deserving infrastructure requirements.

2) With the rising trends in man-hour requirements, are we staffed to meet future demands? While the rising unscheduled maintenance demands will in themselves cause a significant burden, additionally, it is important to consider additional requirements for time-demands placed on our craftsmen. Increased deployments for military personnel, increased training requirements, and work order executions are but just a few examples of increased demands for time.
3) Given the data in the report and the above two questions, has the civil engineer community embraced the right corporate strategy? Civil Engineers pride themselves on maintaining installations that not only meet mission requirements but also provide first class living and work environments to improve quality of life for military members and their families. While we will no doubt continue to strike a balance between mission requirements and quality of life projects, it might be worthwhile to develop an overall strategy that clearly outlines funding priorities.
4) This data is for AFMC, how does the data look for other MAJCOMs? Air Force wide? How are bases doing? Engineer leadership may find a great deal of benefit benchmarking between Major Commands and between bases. Sharing best practices on infrastructure investment may help spread improvements across the Air Force.
5) We rely on a number of organizations to enter data into our database systems; how standardized is our data tracking? Civil Engineers do maintain several databases for storing critical investment and work requirement information. During the course of data analysis, we did notice anomalies in the data sets

that may cast some doubt on the overall data accuracy. If the CE community finds value in managing using data analysis, it would be worthwhile to review data input standardization across the entire CE community.

Recommended Future Research

As a follow on to this research effort and to help answer some the operation relevance questions raised above, there are several areas we recommend for future research.

1) While we looked at the overall trends and built an overarching model for the Air Force Material Command, we do not have any other commands with which to compare the findings. Recommend conducting similar research on the other Major Commands to be able to not only make comparisons between bases but also better infer overall trends for the entire Air Force Infrastructure.
2) During this research design, we hoped to obtain data on specific infrastructure systems such as electrical, plumbing, etc. This was not possible because the data base managers at Gunter do not store this system level information. Recommend a system by system analysis, to allow for better comparison between infrastructure investment and unscheduled maintenance. For example, it may be worthwhile to study investments in electrical systems and evaluate the impact on unscheduled electrical maintenance. In this analysis it would also be important to separate investment projects into those projects intended to maintain or improve (i.e. recurring work program, sustainment and restoration) what we already have and those which could be adding

additional infrastructure (i.e. modernization), in effect creating additional possible failure points.

3) In this research, we analyzed data from seven bases for the years 2001-2007. We were unsuccessful in obtaining earlier data and while we had initially collected the data of eight Air Force Materiel Command installations, the information for one location was discarded from the analysis as it was found to be unreliable data. Recommend future analysis on this subject be performed with data for more years and more bases.
4) This research has only analyzed bases in Air Force Material Command and has not considered whether they are maintained by government employees or by a third party contractor. Recommend analysis be conducted considering different engineering operations.

Conclusion

The amount of resources required to address infrastructure failures on United States Air Force Materiel Command installations exhibits a concerning upward trend over the past seven years. For the seven locations in this study, total man-hours rose from 201,098 in FY01 to 1,094,778 hours in FY07 and total costs increased from $15,539,830 in FY01 to $65,242,772 in FY07. This situation must be considered in an environment of increasingly constrained budgets for the foreseeable future. Therefore, tools for optimizing infrastructure investment and successfully advocating for the resources to do so are essential.

The research described in this report developed predictive models providing a three-year forecast of emergency, urgent, and routine unscheduled maintenance man-hours and funding requirements. The models presented account for 35-80% of the variability in the requirements and further research can improve upon the accuracy and predictive power of these models. The correlation analysis presented challenges conventional wisdom regarding the impact of various types of infrastructure investment and their impact upon future infrastructure failures. Admittedly, this report is rooted in a limited dataset and should be further evaluated through follow-on research efforts.

Overall, this report suggests Air Force leadership can use quantitative analysis to develop decision-making and funding justification tools. Future unscheduled maintenance man-hour and funding requirements can be predicted with statistical significance and a degree of certainty based upon known various forms of infrastructure investment. Further, through this analytical process, enhanced strategy for optimal resource allocation can be identified resulting in reduced infrastructure failures and improved mission effectiveness.

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Vita

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